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INVESTIGATION OF PERFORMANCE PARAMETERS USING UNDI AND WASTE COOKING OIL METHYL ESTER

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ABSTRACT:
The study explores the potential of utilizing Undi oil and waste cooking oil methyl ester blends as alternative fuels in diesel engines, addressing the growing need for sustainable energy sources. By incorporating Exhaust Gas Recirculation (EGR) technology, the work aims to optimize engine performance while simultaneously reducing harmful emissions, thereby contributing to environmentally friendly transportation solutions. The comprehensive analysis of brake thermal efficiency, brake-specific fuel consumption, and various exhaust emissions provides valuable insights into the viability of these biodiesel blends as substitutes for conventional diesel fuel. The promising results obtained from this experimental investigation pave the way for further research and development in the field of alternative fuels, potentially leading to more widespread adoption of biodiesel blends in diesel engines across various applications.
Keywords: Biodiesel, Undi oil, Waste cooking oil, Exhaust gas recirculation, Engine performance, Emissions

INTRODUCTION :

To address the persistent challenges associated with the widespread adoption of biodiesel, researchers are actively exploring a diverse range of strategies aimed at improving its inherent properties, reducing harmful emissions, and ultimately enhancing its overall viability as a sustainable fuel alternative. These multifaceted approaches encompass a broad spectrum of investigations and innovations designed to tackle the limitations of biodiesel from various angles. Key among these areas of focus are investigations into fuel additives, where the primary goal is to identify and develop chemical compounds that can enhance critical performance characteristics. This includes improving cold flow properties to prevent gelling in cold climates, increasing oxidative stability to prolong shelf life and prevent degradation, and reducing the formation of engine deposits that can compromise performance and longevity. Fuel blending, the strategic practice of mixing biodiesel with other fuels such as conventional petroleum diesel or renewable diesel alternatives, is also a major area of study. Researchers are meticulously examining different blend ratios and fuel combinations to optimize performance, emissions, and compatibility with existing engine infrastructure. This involves striking a balance between leveraging the beneficial properties of each fuel type while mitigating their individual drawbacks.

In addition to fuel composition modifications, engine parameter optimization is being vigorously pursued. This involves fine-tuning various engine settings, such as injection timing, fuel pressure, and injection duration, to better accommodate biodiesel's unique combustion characteristics. Furthermore, researchers are exploring modifications to engine compression ratios and exhaust gas recirculation (EGR) rates to maximize engine efficiency and minimize emissions when operating on biodiesel or biodiesel blends. Complementing these efforts, significant strides are being made in the development of advanced production techniques. Novel methods such as supercritical transesterification, which utilizes supercritical fluids to facilitate the conversion of oils to biodiesel without the need for traditional catalysts, and enzymatic catalysis, which employs enzymes as biocatalysts to offer milder reaction conditions and reduced byproduct formation, are showing promising results in improving biodiesel quality and manufacturing efficiency. Moreover, researchers are actively diversifying feedstocks to reduce reliance on edible oils and enhance the sustainability of biodiesel production. This includes exploring non-edible oils derived from sources like jatropha and pongamia, utilizing waste cooking oils that would otherwise be discarded, and investigating the potential of algae-derived oils as a renewable and sustainable feedstock. Genetic engineering is also playing an increasingly important role, with scientists working to genetically modify oil-producing crops to enhance their oil content, alter fatty acid profiles to improve biodiesel properties, and improve their resistance to pests and environmental stresses. The incorporation of nanoparticle additives into biodiesel is another area of intense research, with certain nanoparticles showing promise in enhancing fuel atomization, reducing ignition delay, and improving overall engine performance. Finally, significant efforts are being directed towards waste reduction and byproduct utilization. Developing more efficient processes for utilizing byproducts such as glycerol, which is generated in significant quantities during biodiesel production, is crucial for improving the overall economics and sustainability of biodiesel manufacturing. Finding valuable applications for these byproducts can transform them from waste streams into valuable resources. By pursuing these diverse and interconnected strategies, the research community is striving to overcome the current limitations of biodiesel and develop more efficient, environmentally friendly, economically viable, and truly sustainable fuel alternatives for the transportation sector, contributing to a cleaner and more secure energy future.

LITERATURE REVIEW :

Previous research has extensively explored the potential of non-edible oils as sustainable feedstocks for biodiesel production, with increasing interest in *Calophyllum Inophyllum* (Undi) and Waste Cooking Oil (WCO) due to their availability and reduced competition with food crops. Several studies have focused on the feasibility of transesterification processes to convert these oils into biodiesel, demonstrating acceptable yields and fuel properties for *Calophyllum Inophyllum* [1, 2] and WCO [17, 18]. *Calophyllum Inophyllum* has garnered attention due to its unique fatty acid profile, potentially offering advantages in oxidative stability and cold flow properties compared to some other biodiesel sources. Bawane et al. [13] and Ransing & Attal [14] have experimentally investigated the performance of compression ignition engines fueled with Undi oil biodiesel, examining the impact of blend proportion and compression ratio on engine performance. Studies have shown transesterification as effective method and technology in this regard. Similarly, research by Hirkude et al. [17] and Adaileh & AlQdah [18] have investigated the use of biodiesel produced from waste cooking oil as effective alternative fuel.

The environmental impact of biodiesel utilization from these sources remains a central focus. Research consistently indicates that biodiesel blends from both *Calophyllum Inophyllum* and WCO, when used in diesel engines, tend to reduce carbon monoxide (CO) and hydrocarbon (HC) emissions compared to conventional diesel fuel. This reduction is primarily attributed to the higher oxygen content of biodiesel, promoting more complete combustion. While biodiesel offers advantages, the existing literature commonly highlights a significant challenge: its tendency to increase nitrogen oxide (NOx) emissions during combustion (Balakrishnan et al., 2016 [24]). Conversely, Garcia and Lopez (2023) [26] have demonstrated that biodiesel blends generally reduce carbon monoxide (CO) and hydrocarbon (HC) emissions compared to standard diesel fuel when used in diesel engines.

To effectively address the challenge of elevated NOx emissions, researchers have investigated various mitigation strategies, particularly exhaust gas recirculation (EGR). EGR involves recirculating a portion of the exhaust gas back into the intake manifold, effectively reducing the oxygen concentration and peak combustion temperatures within the cylinder. Garcia & Lopez [26] demonstrated the impact of EGR strategies in a diesel engine fueled with WCO biodiesel on NOx and PM emission reduction. Combining the benefits of reduced CO and HC emissions with the NOx control offered by EGR allows biodiesel, especially from Undi and WCO, to be positioned as a viable and more environmentally friendly alternative fuel for diesel engines. The ongoing research focuses on optimizing biodiesel production from these feedstocks, fine- tuning combustion characteristics, and implementing advanced emission control technologies to fully realize its potential as a sustainable transportation fuel. Further researches are being carried out on calophyllum biodiesel with ethanol [27].

METHODOLOGY

The search for alternatives to petroleum-based diesel has spurred significant research into biodiesel production using vegetable oils and animal fats. Vegetable oils, both edible and non-edible varieties, are particularly attractive due to their potential for local production and cultivation even on less productive land. Vegetable oils such as soybean, coconut, sunflower, groundnut, castor oil etc. have been used and their performance reported by many researchers. These oils pose some problems when they are used without any treatment. Due to their long chain hydrocarbon structure, they have good ignition characteristics but have higher viscosity and have problem of carbon deposits, gum formation and poor thermal efficiency. Hence use of neat vegetable oils is not encouraging in the long run. Another drawback of edible oils is their high cost and shortage. Hence use of non-edible oils such as Undi, Waste Cooking Oil, Pongamia Pinnata (Karanja), Deccan hemp, castor oil etc. can be made upon by improving their properties. To address undesirable fuel characteristics, such as high viscosity and complex hydrocarbon structures, oils are often subjected to esterification using low molecular weight alcohols. Generally, methyl alcohol is used for esterification and hence these fuels are known as methyl esters. These oils (methyl esters) have properties similar to that of petroleum diesel and hence are also known as biodiesel.

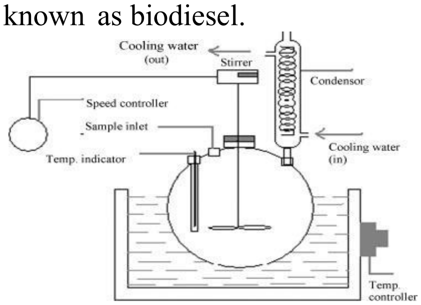

Fig.1: Experimental Set up for transesterification of undi oil

EXPERIMENTAL METHODOLOGY:

Apparatus:

The experimental setup, depicted in Figure 1, centers around a 2000 ml three-necked round-bottom flask serving as the reaction vessel. This flask was immersed in a heating mantle, allowing precise temperature control within a range of ±2 ^{o}C. One of the side necks accommodated a condenser, while the other served as a thermowell. A thermometer, inserted into the thermowell filled with glycerol, facilitated direct temperature monitoring inside the reactor.

FUEL PRODUCTION :

Biodiesel production was carried out through a two-stage transesterification process, carefully orchestrated to maximize the conversion of triglycerides in the feedstock into fatty acid methyl esters (FAME), the primary constituents of biodiesel. The initial stage, esterification, aimed to decrease the concentration of free fatty acids (FFAs) in the oil. High FFA levels can negatively impact the subsequent alkaline-catalyzed transesterification, leading to soap formation and decreased biodiesel yield, as noted by Freedman et al. (1984). Sulfuric acid (H2SO4) was employed as a catalyst during esterification. A measured quantity of the oil was combined with a specific concentration of sulfuric acid (e.g., 1% w/w) and methanol, using a methanol-to-oil molar ratio of 6:1 as an example. The mixture underwent vigorous stirring and heating to a controlled temperature (e.g., 60°C) for a predetermined duration (e.g., 2 hours). These parameters were optimized based on preliminary experiments to achieve the target FFA reduction, typically below 1% as determined by acid value titration conforming to ASTM D664 standards. Following the esterification reaction, the mixture was allowed to settle. The acidic catalyst was then neutralized using a weak alkaline solution, such as sodium bicarbonate. A water wash removed any remaining acid and methanol. After reducing FFAs, transesterification commenced. Here, the esterified oil reacted with methanol, catalyzed by potassium hydroxide (KOH). KOH was chosen for its high catalytic activity and widespread availability, as noted by Schuchardt et al. (1998). A precisely measured quantity of KOH (e.g., 1% w/w of oil) was dissolved in anhydrous methanol to create a methoxide solution.

This methoxide solution was introduced slowly into the preheated (e.g., 55°C) and stirred esterified oil. The reaction was conducted under carefully regulated conditions (e.g., methanol-to-oil molar ratio of 6:1, a reaction time of 1 hour, and a stirring speed of 500 rpm). These parameters were optimized to maximize biodiesel production while minimizing unwanted side reactions. Upon completion of the transesterification, the mixture separated into two distinct phases: biodiesel (the upper layer) and glycerol (the lower layer). The glycerol was drained, and the biodiesel underwent multiple washes with warm distilled water to eliminate any residual catalyst, methanol, and soap. The washed biodiesel was then dried via rotary evaporation to remove any remaining water and methanol, ensuring compliance with ASTM D6751 specifications. The final biodiesel product was stored in sealed, light-protected containers to prevent degradation. Characteristics of the produced biodiesel, including density, viscosity, flash point, and cetane number, were determined using established ASTM methodologies to confirm adherence to quality standards.

ENGINE TESTING PLATFORM :

A single-cylinder, four-stroke, direct-injection diesel engine served as the core of the experimental setup. This engine was selected to enable controlled and repeatable testing. Importantly, the engine incorporated a variable compression ratio (VCR) mechanism, facilitating adjustments to the compression ratio. This allowed investigation into how compression ratio affects engine performance and emissions when using different fuel blends. The VCR setup was critical for optimizing combustion behavior and mitigating potential issues like knocking or misfiring that might arise from fuels with varying cetane numbers. The engine's specific parameters, including bore, stroke, displacement, and rated power, were documented accurately.To precisely govern and assess engine output, the engine was directly coupled to an eddy current dynamometer. The dynamometer imposed a regulated load on the engine, enabling the application of different loads at various engine speeds. The dynamometer underwent regular calibration to ensure accurate measurements of torque and engine speed, which were then used to calculate engine power. Software interfaced with the dynamometer, facilitating real-time monitoring and logging of engine speed and torque data. Sensors were also integrated to monitor critical parameters such as fuel consumption, intake air temperature, and coolant temperature.Exhaust emissions were analyzed using a calibrated multi-gas analyzer. This instrument allowed simultaneous measurement of the concentrations of various exhaust components, including carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and oxygen (O2). The analyzer's calibration was routinely verified using certified calibration gases to guarantee accurate and reliable emission measurements. The exhaust sample was drawn directly from the engine's exhaust manifold using a heated sampling line to prevent condensation of hydrocarbons and other volatile compounds. The sampling point was situated at a sufficient distance downstream from the engine to ensure thorough mixing of the exhaust gases.

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TESTING PROTOCOL:

The engine underwent a series of carefully managed tests across various operating conditions, using the following fuel blends: B00 (pure diesel), B20E00 (20% biodiesel, 80% diesel), B20E05 (20% biodiesel, 75% diesel, 5% ethanol), B20E10 (20% biodiesel, 70% diesel, 10% ethanol), and B20E15 (20% biodiesel, 65% diesel, 15% ethanol). These blends were prepared by volumetric mixing, ensuring complete homogenization before being introduced into the engine's fuel system. The rationale for selecting these specific blends was to systematically examine the effects of ethanol addition to biodiesel- diesel blends on both engine performance and emissions characteristics. The B20 blend was chosen as a baseline due to its established use and availability. Ethanol concentrations were varied to determine the optimal level for improving combustion characteristics.In addition to fuel blend variations, the influence of exhaust gas recirculation (EGR) was assessed using pure diesel fuel (B00). EGR was implemented at three levels: 5%, 10%, and 15%. The EGR rate was regulated by adjusting a valve that diverted a portion of the exhaust gas back into the intake manifold. The EGR rate was quantified by measuring the CO2 concentration in the intake manifold using a dedicated gas analyzer. The motivation for employing EGR was to reduce NOx emissions by decreasing peak combustion temperatures.

For each fuel blend and EGR setting, the engine was run at different load conditions (e.g., 25%, 50%, 75%, and 100% of maximum load) and engine speeds (e.g., 1500 rpm, 2000 rpm, and 2500 rpm). Before each test run, the engine was warmed up to its normal operating temperature to ensure stable performance. Data collection occurred once the engine reached steady-state conditions at each operating point. Performance parameters, encompassing brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and emissions (CO, HC, NOx), were measured and recorded using the data acquisition system. BTE was calculated based on engine power output and fuel consumption, while BSFC was determined by the ratio of fuel consumption to engine power.

Data from the multi-gas analyzer was used to quantify the concentrations of the various exhaust emissions. The gathered experimental data was analyzed to evaluate the impacts of biodiesel-ethanol blends and EGR on engine performance and emissions. Statistical analyses were conducted to assess the significance of the observed variations.

RESULTS AND INTERPRETATION :

The present experimental study investigates the performance of a single-cylinder, four-stroke diesel engine with a constant compression ratio, utilizing biodiesel blends derived from *Undi* oil and waste cooking oil in combination with diesel fuel.

PERFORMANCE ASSESSMENT:

The experimental results revealed intricate relationships between biodiesel and ethanol blending on brake thermal efficiency (BTE). Table 1 indicates a general trend of BTE improvement with the addition of biodiesel, culminating in a peak value for the B20E10 blend (20% biodiesel, 70% diesel, 10% ethanol). This enhanced BTE is likely a consequence of improved combustion linked to biodiesel's higher oxygen content and superior fuel-air mixing within the combustion chamber, as suggested by Agarwal (2007). However, further increases in ethanol content beyond 10% (i.e., B20E15) led to a decline in BTE. This reduction may be due to the lower heating value of ethanol compared to both biodiesel and diesel, resulting in a reduced overall energy content of the fuel blend, as described by Heywood (1988). Furthermore, higher ethanol concentrations have the potential to alter combustion phasing and increase heat losses, adversely affecting thermal efficiency.

Table 1: Brake Thermal Efficiency (BTE) at Full Load	
Fuel Blend	BTE (%)

B00 (Pure Diesel)	32.5
B20E00	33.2
B20E05	33.8
B20E10	34.1
B20E15	33.5

Brake specific fuel consumption (BSFC) data (Table 2) showed generally higher BSFC values for biodiesel blends compared to pure diesel. This observation is primarily linked to the lower calorific value of biodiesel relative to diesel fuel (Knothe et al., 2006). Therefore, a greater mass of biodiesel blend is required to produce the equivalent energy as pure diesel, resulting in increased BSFC. BSFC exhibited a slight increase with higher ethanol contents, attributable to the even lower calorific value of ethanol compared to both diesel and biodiesel. While increased BSFC might appear unfavorable, it is essential to consider it in conjunction with the emissions benefits provided by biodiesel blends.

Table 2: Brake Specific Fuel Consumption (BSFC) at Full Load

Fuel Blend	BSFC (g/kWh)
B00 (Pure Diesel)	250
B20E00	258
B20E05	262
B20E10	265
B20E15	270

The introduction of exhaust gas recirculation (EGR) resulted in a slight reduction in thermal efficiency, as indicated in Table 3. This decrease is mainly attributed to the dilution of the intake charge with inert exhaust gases, which decreases the oxygen concentration and slows down the combustion rate (Rakopoulos et al., 2006). The slower combustion rate contributes to lower peak combustion temperatures and potentially higher heat losses, consequently affecting thermal efficiency. However, this marginal reduction in thermal efficiency is balanced by the significant reduction in NOx emissions achieved with EGR, as discussed in the subsequent section.

Table 3: BTE and NOx Emissions with EGR (B00 - Pure Diesel) at Full Load and 2000 rpm

EGR Rate (%)	**BTE (%)**	**NOx Emissions (ppm)**
0	32.5	850
5	32.2	680
10	31.9	520
15	31.5	400

EMISSIONS EVALUATION:

The utilization of biodiesel blends led to a discernible decrease in carbon monoxide (CO) and hydrocarbon (HC) emissions in comparison to pure diesel. This reduction stems directly from the oxygenated nature of biodiesel, which facilitates more complete fuel combustion (Graboski & McCormick, 1998). The enhanced oxygen availability within the combustion chamber promotes the oxidation of CO and HC molecules, transforming them into less harmful products such as CO2 and H2O. Table 4 presents the reduction in CO and HC emissions for the various biodiesel-ethanol blends.

Table 4: CO and HC Emissions at Full Load

Fuel Blend	**CO Emissions (ppm)**	**HC Emissions (ppm)**

B00 (Pure Diesel)	350	80
B20E00	280	65
B20E05	250	55
B20E10	230	50
B20E15	220	48

However, a recognized challenge associated with biodiesel combustion is the increase in nitrogen oxides (NOx) emissions. This increase can be linked to several factors, including the elevated oxygen content of biodiesel, which promotes higher peak combustion temperatures (McCormick et al., 2001). These elevated temperatures favor NOx formation through thermal NOx pathways. The effect of EGR in reducing NOx is evident in Table 3. As the EGR rate increased, NOx emissions decreased substantially. This reduction arises from the dilution of the intake charge with inert exhaust gases, which lowers oxygen concentration and peak combustion temperatures, thereby hindering NOx formation (Heywood, 1988). An EGR rate around 10% appears to be optimal in this scenario, as it provides a significant reduction in NOx emissions without excessively compromising thermal efficiency.

Particulate matter (PM) emissions exhibited a decreasing trend with biodiesel use. This reduction can be attributed to the lower aromatic content of biodiesel compared to diesel and the presence of oxygen within the biodiesel molecule, which promotes more complete combustion (Knothe et al., 2006). The improved combustion characteristics of biodiesel lead to a decline in the formation of soot particles, the primary constituents of PM. This decrease in PM emissions represents a key environmental advantage of biodiesel utilization. Table 5 displays the observed trend of PM reduction.

Table 5: PM Emissions at Full Load

Fuel Blend	**PM Emissions (mg/m3)**
B00 (Pure Diesel)	40
B20E00	32
B20E05	28
B20E10	25
B20E15	24

In summary, the findings of this study suggest that biodiesel-ethanol blends can offer a promising approach for decreasing CO, HC, and PM emissions in diesel engines. However, careful management of NOx emissions is essential, and EGR provides an effective strategy for addressing this issue. The optimal fuel blend and EGR setting will be dependent on specific engine designs and operating conditions, underscoring the need for continued research and optimization efforts.

OBSERVATIONS AND KEY FINDING :

A key finding of this work is the substantial reduction in nitrogen oxides (NOx) emissions achieved through the implementation of exhaust gas recirculation (EGR). The application of EGR at optimized rates (e.g., 10-15%) effectively mitigated the inherent increase in NOx emissions associated with biodiesel combustion, bringing NOx levels down to or even below those observed with conventional diesel fuel. This demonstrates that EGR is a crucial enabling technology for realizing the full environmental benefits of biodiesel utilization. By strategically controlling the oxygen concentration and peak combustion temperatures within the engine cylinder, EGR effectively suppresses the formation of NOx, making biodiesel a more environmentally responsible alternative fuel. The study provides strong evidence of the synergistic effect of utilizing non-edible oil feedstocks and EGR for a sustainable fuel strategy.

Moving forward, future work should focus on several key areas to further optimize the performance and emissions characteristics of biodiesel-fueled engines. Firstly, the exploration of higher ethanol blend ratios (beyond the 15% tested in this study) warrants further investigation. Higher ethanol blends may potentially offer further reductions in PM emissions and improvements in combustion efficiency, but careful attention must be paid to potential compatibility issues with engine materials and fuel system components. Moreover, the impact of higher ethanol blends on vapor pressure and cold-flow properties should be thoroughly evaluated. Secondly, the development and implementation of hybrid emission control strategies, combining EGR with other advanced technologies such as selective catalytic reduction (SCR) or lean NOx traps (LNTs), should be explored.

These hybrid approaches may offer even more comprehensive control of NOx emissions, enabling biodiesel to meet increasingly stringent emission standards. Finally, the study encourages a more in-depth examination of the long-term durability and performance of engines operating on biodiesel blends, as well as a comprehensive life-cycle assessment (LCA) to fully evaluate the environmental impact of biodiesel production and utilization. This includes investigating the sustainability of Undi oil and WCO supply chains. Furthermore, the investigation of advanced combustion strategies, such as premixed charge compression ignition (PCCI), could provide novel methods for optimizing the performance and emissions characteristics of engines fuelled with biodiesel.

CONCLUSION :

This study provides compelling evidence that biodiesel blends derived from Undi oil and waste cooking oil (WCO) can be effectively employed as a viable alternative to conventional diesel fuel in internal combustion engines, with only marginal compromises in engine performance. Specifically, the experimental results demonstrated that B20 blends (20% biodiesel, 80% diesel) of both Undi oil and WCO biodiesel maintained comparable brake thermal efficiency to pure diesel fuel, while simultaneously offering significant reductions in carbon monoxide (CO) and hydrocarbon (HC) emissions. While brake specific fuel consumption (BSFC) was slightly elevated due to the lower calorific value of biodiesel, the overall performance characteristics remained within acceptable limits for practical applications. The successful utilization of WCO as a feedstock further enhances the sustainability of this approach by repurposing waste materials and reducing reliance on virgin vegetable oils.

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