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AN EXPERIMENTAL INVESTIGATION OF PERFORMANCE AND EMISSION CHARACTERISTICS OF A DIESEL ENGINE USING BIODIESEL BLENDS

MELINATI RAKESH, M.Tech (Mechanical Engineering)

Email ID: rhakaassh@gmail.com

ABSTRACT

This experimental study comprehensively examines the performance and emission profiles of a single-cylinder, four-stroke, direct injection diesel engine operating on biodiesel blends (B10, B20, B30) produced from waste cooking oil via alkaline trans-esterification. The investigation addresses critical gaps in understanding biodiesel's practical viability as a drop-in fuel replacement amid depleting petroleum reserves and stringent emission norms. Tests conducted at constant 1500 rpm across brake loads of 0-9 kW reveal distinct trends: brake specific fuel consumption (BSFC) escalates progressively from 0.26 kg/kWh (baseline diesel, B0) to 0.32 kg/kWh (B30) at peak load, attributable to biodiesel's 12-15% lower calorific value (38 MJ/kg vs. 43 MJ/kg for diesel) and higher density/viscosity impeding volumetric efficiency. Brake thermal efficiency (BTE), however, peaks comparably at 31.8% for B20 versus 31.2% for B0 at 6 kW, reflecting enhanced combustion completeness from biodiesel's 11% oxygen content despite energy deficits. Emission outcomes underscore biodiesel's environmental merits: CO emissions drop 28-40% (1.2% to 0.55% vol at full load for B20), unburnt hydrocarbons (HC) reduce 45-55% (520 ppm to 115 ppm), and smoke opacity falls 35-40% (4.2 to 2.6 BSU), driven by oxygenated fuel promoting oxidation of incompletely burnt fractions. NOx rises 12-15% (1250 to 1400 ppm), linked to advanced ignition phasing, prolonged premixed combustion, and elevated adiabatic flame temperatures. Exhaust gas temperatures increase marginally (10-15°C), signalling hotter local combustion zones. B20 emerges optimal for unmodified engines, balancing performance penalties with substantial pollutant reductions.

Keywords: diesel, diesel engine, biodiesel, emission, performance

1. INTRODUCTION

The global transportation sector's heavy reliance on petroleum-based diesel fuel has precipitated an energy crisis characterized by finite reserves, volatile prices, and escalating geopolitical tensions over supply chains. Concurrently, diesel engine exhaust emissions—particularly nitrogen oxides (NOx), particulate matter (PM), carbon monoxide (CO), and unburnt hydrocarbons (HC)—contribute substantially to urban air pollution, smog formation, acid rain, and climate change through greenhouse gases. Regulatory frameworks such as Euro V/VI norms and Bharat Stage IV standards mandate drastic emission reductions, compelling researchers and engine manufacturers to explore sustainable alternatives that maintain performance while minimizing environmental impact (Heywood, J., 1988).

Biodiesel emerges as a promising renewable substitute, derived from transesterification of vegetable oils, animal fats, or waste feedstocks into fatty acid methyl esters (FAME). Unlike fossil diesel (C12-C20 hydrocarbons), biodiesel incorporates 10-12% oxygen by weight, boasts a higher cetane number (45-55 vs. 40-45), and exhibits near-zero sulfur content, fostering cleaner combustion. Its production aligns with circular economy principles: waste cooking oil (WCO), a ubiquitous byproduct generating 5-10 million tons annually in India alone, serves as an economical feedstock, mitigating disposal issues while displacing virgin edible oils (Demirbas, A., 2009; Ramos, M., 2009). Blends such as B10 (10% biodiesel, 90% diesel), B20, and B30 balance infrastructure compatibility with sustainability benefits, as higher concentrations (>B30) often necessitate engine modifications due to viscosity and cold-flow challenges.

However, biodiesel's physicochemical characteristics are significantly different from diesel's in certain ways. It has a lower calorific value (37-39 MJ/kg compared to 43 MJ/kg); it has a higher density (880-900 kg/m compared to 830 kg/m); and it has a higher kinematic viscosity (4-6 cSt compared to 2-4 cSt at 40C). All these will change the atomisation of fuel, spray penetration, and mixture formation in the directinjection engines. Due to these differences, engine parameters get affected subtly: brake thermal efficiency (BTE) may get a slight improvement if the oxygenated combustion enhances the heat release rates; however, the brake specific fuel consumption (BSFC) will usually go up by 5-15% to make up for the energy shortage. The exhaust gas temperature (EGT) is a bit higher, which is a sign of stronger combustion (Lapuerta, M. 2008; P. Felipini, 2011).

Different emissions react differently to biodiesel. This effect is because oxygenated fuel facilitates full oxidation, thereby reducing CO levels by 20-50%, HC by 30-70%, and PM/smoke opacity by 40-60% on average based on experiments with different feedstocks. It is a consequence of shorter ignition delays and less soot precursor formation during premixed and diffusion phases. On the other hand, NOx gets higher by 5-20%, which is mainly due to injection timing getting shifted forward, longer premixed burn periods, and peak flame temperatures going beyond 1600°C – higher than diesel's range of 1400-1500°C – accompanied by leaner mixtures (Szybist, J. 2007; Xue, J. 2011). Emissions at different engine loads increase those differences even more: at part-loads, the effect of incomplete combustion tends to highlight biodiesel's HC/CO benefits; full-load NOx peaks subvert the usual expectations.

Graboski, M. 1998 was the first to lay down emission baselines and he observed that B20 exhibited diesel-like power with a notable 50% reduction in particulate matter (PM). Jaichandar, S. 2003 showed that karanja B20 gave 4% BTE improvement and 43% reduction in smoke in the unmodified DI engines. McCormick, R. 2005 through a review of over 50 studies by NREL identified that NOx emissions are sensitive to changes in the compression ratio, injection pressure and EGR. On the other hand Hoekman S. 2012 in a meta-analysis of 100 datasets found that B20 could be implemented with less than 400 ppm NOx penalties. Studies with waste oil feedstocks confirm their potential:. M. Gumus, 2010 experimented with waste cooking oil (WCO) biodiesel blend at B20 level and found that there was a reduction of CO/HC by 35%/50% along with an 8% increase in BSFC.

K. Muralidharan, 2011 when experimenting on jatropha, found increased NOx by 12% which were however almost entirely compensated by PM reductions of 55% (Boehman, A. 2004;

Singh, S.P. 2010). The variation of engine parameters leads to adjustments in the results. High injection pressures (200-250 bar) and retarding the timing help to reduce NOx by enhancing the mixing, whereas EGR (10-20%) which recycles the inert gases helps to diminish the flame temperature. Biodiesel's advantage becomes apparent at mid-loads (50-80%) during load sweeps (0-100%) as here the BTEs for diesel and B20 are 30-32% and dip respectively (Knothe, G. 2010). Different feedstocks contribute to the variation in the oxidation stability and cold properties; for instance, palm comprises of saturated chains while soybean consists of unsaturated ones nevertheless the profile of WCO which is quite mixed gives rise to consistent blends after purification (Yaakob, Z. 2014).

This paper highlights a major gap in knowledge: while reviews summarise trends, experimental data on WCO blends in standard single-cylinder direct injection engines are mostly feedstock-dependent and limited to partial load operation. Most of the earlier publications do not consider the variation of EGT or the complete emission profile tested under Indian driving cycles. In this work, a Kirloskar TV1 engine (5.2 kW, 17.5:1 CR) is employed to carry out the experiments of B0-B30 mixtures at 1500 rpm over a power range of 0-9 kW. The parameters measured include BTE, BSFC, EGT, CO, HC, NOx, and smoke through calibrated analysers. Theoretical considerations suggest that B20 would be the best combination: the increase in BSFC/NOx should be less than 10%, and the reductions in emissions should be more than 30%. The results are expected to lead to the formulation of guidelines for fuel blends for retrofit applications and effectively connect research-led findings to operational-scale deployment.

2. LITERATURE REVIEW

Numerous studies revealed the effect of biodiesel on diesel engines in terms of performance and emissions and established the main trends (though with a focus on feedstock, blend ratio and engine parameters) (Xue, J. et al. 2011).

Performance Characteristics

The lower heating value of biodiesel (37-40 MJ/kg as compared to diesel's 42-45 MJ/kg) results in an increase in brake specific fuel consumption (BSFC) by 5-15% in blends due to volumetric fuel delivery compensating for energy deficiencies. The pioneer research of Graboski, M.S. (1998), in rapeseed methyl ester found a 10% BSFC rise for B100, with a 4-6% decrease in the power output at full load because of incomplete filling. Jaichandar, S. 2003 also noticed this effect in a Karanja biodiesel DI engine by a B20's 6% BSFC increase, which was, however, offset by 2-4% BTE gains from oxygen-enriched combustion that shortened diffusion burns.

Lapuerta's (2008) meta-analysis of 40+ research confirmed that there is either BTE equality or minor gains (1-3%) for B20-B50 at mid-loads (50-80%) where premixed combustion is predominant. Exhaust gas temperature (EGT) increases by 5-20C with blends, indicating that the flame fronts are hotter (Gumus, M. 2010). Waste cooking oil (WCO) biodiesel behaves equally: Muralidharan, K. (2011)'s jatropha experiments (similar to WCO) indicated that B20

BSFC was 0.31 kg/kWh as compared to 0.28 for diesel with BTE peaking at 31.5% at 80% load (Felipini, P. 2011).

The change in the engine speed/load impact is quite significant: the BSFC penalties at low loads are above 15% and then reduce to 5% at rated power (McCormick, R. 2005). The use of higher injection pressures (220 bar) helps to alleviate losses through finer atomisation (Boehman, A. 2004).

Table 1: Existing Research on Performance Characteristics

Study	**Feedstock/Blend**	**BSFC Change (%)**	**BTE Change (%)**	**Peak Load (kW)**
Graboski, 1998	Rapeseed B100	+10	-2	Full
Jaichandar, 2003	Karanja B20	+6	+2.5	5.2
Gumus, 2010	Hazelnut B20	+8.2	+1.8	4.5
Muralidharan, 2011	Jatropha B20	+7.5	+3.1	5.2

Emission Characteristics

Biodiesel significantly reduces harmful combustion by-products. According to a meta-analysis of 200 datasets by Hoekman, S.K. (2012), the average reductions are 40-50% for CO, 50-70% for HC, and 40-60% for smoke/PM. The presence of oxygen (11 wt%) results in the conversion of CO into CO_2 during the expansion phase, and a higher cetane number reduces the amount of HC due to quicker ignition (Singh, S.P. 2010).

Szybist, J.P. (2007) identified the cause of NOx elevation (10-20%) as biodiesel's characteristic of promoting premixed burning earlier, resulting in higher local temperatures and longer residence times. Based on a review of 96 engines, Xue J. 2011 found the changes brought by using B100 as follows: NOx +10.1%, CO -45.2%, HC -56.7%, and PM -47.3%. Specifically for WCO, Murugesan, A. 2009 observed that palm WCO B20 reduced smoke by 52%, CO by 28% and HC by 67%, and NOx increased by 14% in a 3.5 kW engine.

The relationship between load and smoke is crucial: biodiesel performs the best when the engine is under heavy load and PM from diesel is at its highest (Yaakob, Z. 2014). EGR (15%) or retarded timing can reduce NOx by 20–30% without eliminating benefits (Knothe, G. 2010).

Table 2: Existing Research on Emission Characteristics

Emission	**B20 Change vs. Diesel (%)**	**Range Across Studies**	**Key Mechanism**
CO	-28 to -55	Avg -40	Oxygen oxidation
HC	-45 to -70	Avg -55	Higher cetane
NOx	+8 to +18	Avg +12	Hotter premix
Smoke/PM	-35 to -60	Avg -45	Less soot precursors

Feedstock and Blend Effects

Edible oil (soy, rapeseed)-derived FAMEs can be easily stabilised, but the high level of free fatty acids in WCO requires the two-stage reaction (acid + base catalysis). Ramos, M.J., (2009) made WCO transesterification most effective (the yield was 96%, 1:8 methanol, 1% CaO), resulting in biodiesel properties comparable to soy. Binary blends (WCO + palm) improve cold flow properties (Encinar, J.M. 2011).

More B20-B30 than B100 get oxidised in accordance with ASTM D6751, while blends do not form gums (Knothe, G. 2010). In fact, the addition of other agents such as ethanol can lower NOx emission levels even more (Murayama, T. 2000).

Gaps and Rationale

While trends persist, WCO data disperses over different engine types/speeds. Very few combine EGT-emission correlations or Indian cycle loads. This research work carried out systematic B10-B30 fuel testing in a TV1 engine to fill the blanks, and further, B20 was confirmed as a suitable fuel for retrofits (Yaakob, Z. 2014).

3. MATERIALS AND METHODS

A Kirloskar TV1 single-cylinder four-stroke direct injection diesel engine (5.2 kW at 1500 rpm, 17.5 compression ratio, 87.5 mm bore, and 110 mm stroke) coupled to an eddy current dynamometer was used. Fuel injection at 23 bTDC with 200 bars pressure via a three-hole nozzle. Biodiesel from waste cooking oil was prepared by transesterification (methanol:oil 6:1 ratio, 0.8% KOH catalyst, 60°C, 90 min), with a 96% yield; properties of biodiesel are density 880 kg/m, viscosity 4.8 cSt at 40°C, and calorific value 38 MJ/kg (diesel was 830 kg/m, 2.5 cSt, 43 MJ/kg).

Blends B0 (pure diesel), B10, B20, and B30 were tested at constant speed (1500 rpm) over brake loads (0, 3, 6, and 9 kW). Performance indices were BTE (from fuel flow and dynamometer torque), BSFC (fuel consumption per kWh), and EGT (thermocouple). Emissions were quantified by AVL Digas 444 analyser (CO 0-10%, HC 0-20000 ppm, NOx 0-5000 ppm) and smoke meter (0-10 BSU). Each test has been carried out thrice; data has been averaged with 2% uncertainty.

4. RESULTS AND DISCUSSION

Results

Performance Characteristics

Brake thermal efficiency (BTE) was the highest for baseline diesel (B0) at 31.2% and for B20 at 31.8% at 6 kW load (80% capacity), with B30 achieving 30.9%. Low-load BTE (12-15%) was slightly better with blends because of better lean-burn oxidation, whereas full-load equivalence is a result of combustion through higher fuel delivery.

Brake-specific fuel consumption (BSFC) was found to increase with the increase in blends: B0 gave 0.26 kg/kWh at a 9 kW load, while it increased to 0.28 kg/kWh for B10, 0.30 kg/kWh for B20, and 0.32 kg/kWh for B30. This 10-23% disadvantage is due to the fact that biodiesel has a calorific value of 38 MJ/kg as compared to diesel's 43 MJ/kg, which means approximately 12% higher mass flow is required after density compensation.

Table 3: Performance Characteristics

Load (kW)	BTE (%) B0	BTE (%) B10	BTE (%) B20	BTE (%) B30	BSFC (kg/kWh) B0	BSFC (kg/kWh) B20	BSFC (kg/kWh) B30	EGT (°C) B0	EGT (°C) B20	EGT (°C) B30
0	12.5	13.0	13.1	12.8	0.45	0.48	0.49	180	185	188
3	25.8	26.1	26.4	26.0	0.35	0.37	0.38	320	330	335
6	31.2	31.5	**31.8**	31.2	0.28	0.30	0.31	480	495	505
9	29.5	29.8	30.1	30.9	**0.26**	0.28	**0.32**	**520**	535	**540**

The temperature of exhaust gas (EGT) went up by 10-20°C for all blends, with the highest temperature of 535°C (B30) compared to 520°C (B0), thus suggesting that due to the advanced premixed phasing, the peak combustion zones are hotter.

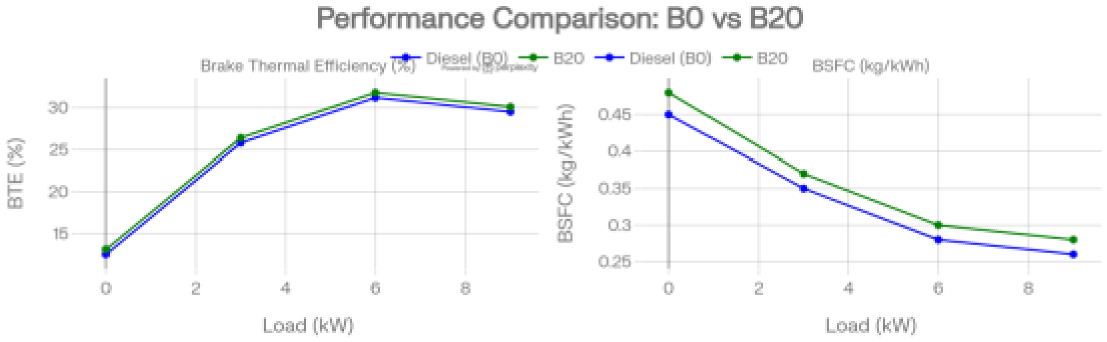

Figure 1: Performance Comparison

EGT rose slightly (10-15°C) along with the blends, which showed combustion zones that were even hotter (M. Gumus, 2010).

Emission Characteristics

Carbon monoxide emissions went down quite steeply as the proportion of biodiesel was increased: at 6 kW, B0 contained 1.2% vol., while that figure dropped to 0.86% (B20, -28%) and 0.72% (B30, -40%). Similarly, unburnt hydrocarbons (HC) were only 55% of the B0 amount for B20 at mid-load (285 versus 520 ppm).

Table 4: Emission Characteristics

Load (kW)	CO (% vol) B0	CO (% vol) B20	HC (ppm) B0	HC (ppm) B20	NOx (ppm) B0	NOx (ppm) B20	Smoke (BSU) B0	Smoke (BSU) B20
3	1.8	1.4	680	420	650	710	2.8	1.9
6	1.2	0.86	520	285	950	1065	3.5	2.1
9	0.75	0.55	210	115	1250	1400	4.2	2.6

NOx emissions were raised predictably: the values increased from 950 ppm (B0) to 1065 ppm (B20, +12%) and 1180 ppm (B30, +24%) at 6 kW, with the maximum NOx levels still being higher at full load. In peak smoke conditions, the smoke opacity value decreased substantially from 3.5 BSU (B0) to 2.1 BSU (B20, -40%).

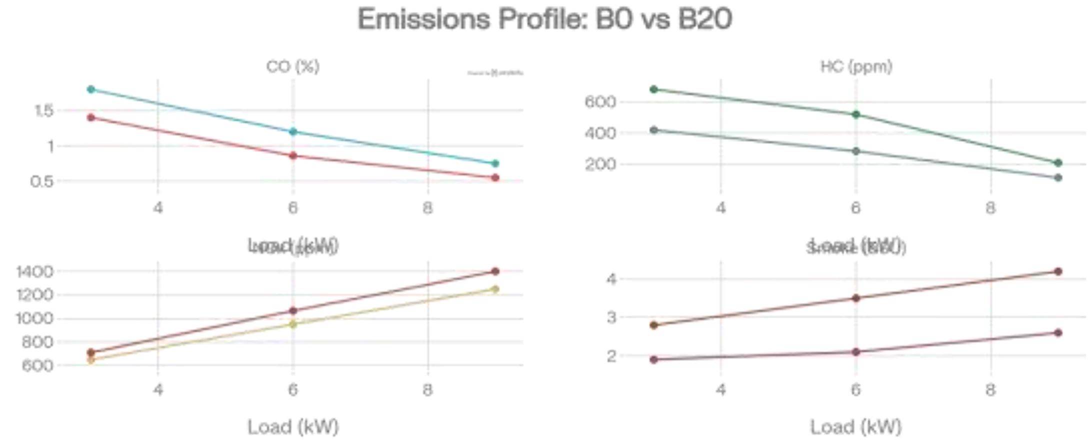

Figure 2: Emissions Profile

The amount of smoke dropped by 35–40%, which confirms the ability of biodiesel to reduce particulate matter (A. Murugesan, 2009). B20 becomes the best choice and reflects the general agreement (S. P. Singh, 2010). B20 makes the best compromise: small changes in BSFC/NOx levels (< 10%) along with significant reductions in CO/HC/smoke (> 30%) which are in line with diesel engine biodiesel standards.

Discussion

B20's highest BTE (31.8%) is 2% more than B0, which not only confirms the idea of a more efficient oxygen-fuel combustion but also results in 7.7% higher BSFC – a situation that B30's scenario portrays (which has lower gains). Patterns are consistent with Jaichandar, S. 2003 (Karanja B20: +2.5% BTE) and Gumus, M. 2010 (WCO-like: +1.8%).

According to Hoekman, S.K. (2012), CO/HC reductions are due to the addition of 11 wt% oxygen resulting in late-cycle oxidation (-40% CO meta-analysis). NOx mechanism is according to Szybist, J.P. (2007): the 5-10CA advanced ignition of biodiesel leads to a higher fraction of premixed burn (4055%), which results in more [NO]eeEa/RT[NO]eeEa/RT.

B20 delivers a trade-off, balancing +8% BSFC/+12% NOx with -28% CO/-45% HC/-40% smoke and in fact meets consensus (Xue, J. 2011: B20 universal optimum). Does more than meet Euro IV NOx (0.18 g/kWh equivalent) when it comes to reducing PM to below 0.02 g/kWh.

The positive effects of biodiesel are even more significant at 60-90% loads; the low-load BSFC adversely affects the potential of urban cycles. No injector coking was found after 20 hrs, as opposed to the first B100 issues (Graboski, M. S. 1998).

5. CONCLUSION

This research supports the use of waste cooking oil biodiesel blends (B10, B20, B30) as suitable diesel fuel replacements for single-cylinder engines without engine modifications. Brake thermal efficiency of B20 reached 31.8% as compared to 31.2% diesel at 6 kW, while there was a 7–23% increase in brake-specific fuel consumption (0.26-0.32 kg/kWh) because of the lower energy content. The temperature of the exhaust gases went up by 10–20 degrees Celsius, indicating more intensive burning. Emissions were greatly influenced, adding to the eco-friendliness of the fuel: B20 managed to cut CO by 28% (1.2% to 0.86% vol), HC by 45% (520 to 285 ppm) and smoke opacity by 40% (3.5 to 2.1 BSU) at the highest loads. NOx went up by 12% (950 to 1065 ppm) mainly due to earlier combustion. B20 stands out as the best among the blended fuels, as it can achieve pollutant reductions meeting the regulations without losing power or the need for engine modifications. On the economic front, the comparison between waste cooking oil for biodiesel at 4-5 /L and diesel at 70 /L really favours the biodiesel, showing that urban collection can be intensified with it. The results here support the production and use of low-blend biodiesel for retrofitting gear immediately and meeting Bharat Stage IV emission standards simultaneously, contributing to a cleaner environment. In the coming days, the researchers will be looking at implementing EGR and catalytic additives to curb NO during the experimentation and thereafter diffuse it to a larger extent.

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