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Investigating the Impact of Fuel Storage, Blend Composition, and Operating Parameters on Diesel Engine Characteristics Using an L16 Orthogonal Array

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Abstract: - The global imperative to reduce dependency on fossil fuels and mitigate environmental pollution has intensified research into sustainable alternatives for compression-ignition (CI) engines. This study presents a comprehensive investigation into the optimization of a single-cylinder CI engine's performance and emission characteristics using B20 ternary biodiesel blends derived from Jatropha, Pongamia, and Waste Cooking Oil (WCO). A robust statistical approach, the Taguchi L16 orthogonal array, was employed to analyze the simultaneous effects of four critical factors at four levels each: blend composition, fuel storage condition, engine load, and injection pressure. The performance metrics evaluated were Brake Specific Fuel Consumption (BSFC) and Brake Thermal Efficiency (BTE), while emission analysis focused on Oxides of Nitrogen (NOx), Carbon Monoxide (CO), and Unburned Hydrocarbons (HC). Analysis of Variance (ANOVA) was conducted on the Signal-to-Noise (S/N) ratios to determine the statistical significance and percentage contribution of each factor. Results indicated that engine load was the most dominant factor influencing BTE (58.31% contribution) and NOx (61.25% contribution). Injection pressure significantly affected BSFC (contributing to a lesser extent than load), CO (39.88%), and HC (42.54%). Adverse storage conditions, particularly elevated temperature and light exposure, were found to degrade fuel properties, leading to a quantifiable deterioration in engine performance and an increase in harmful emissions. A multi-response optimization revealed that while high load and high injection pressure improved thermal efficiency, they severely increased NOx emissions. The final optimized parameters, balancing performance and emissions, were identified as a blend of 50:50 Pongamia + WCO (B20), stored in dark conditions, operating at 75% load and an injection pressure of 200 bar. This study underscores the critical interplay between fuel formulation, storage stability, and engine operating parameters for the practical implementation of biodiesel fuels.

Keywords: *Biodiesel, Taguchi Method, L16 Orthogonal Array, Engine Performance, Exhaust Emissions, Storage Stability, Injection Pressure, Jatropha; Pongamia, Waste Cooking Oil.*

1. Introduction

The dual challenges of depleting petroleum reserves and the escalating environmental impact of fossil fuel combustion have catalyzed a global search for viable, renewable energy sources. For the transport and industrial sectors, which are heavily reliant on compression-ignition (CI) engines, biodiesel has emerged as a particularly promising alternative [1][2]. Derived from renewable biomass, biodiesel is biodegradable, non-toxic, and exhibits combustion properties similar to conventional diesel, allowing its use in existing engines with minimal to no modification [3].

The selection of feedstock for biodiesel production is a critical consideration. First-generation biodiesels, derived from edible oils, have raised concerns regarding the food-versus-fuel debate. [4]. Consequently, research has shifted towards second-generation feedstocks, such as non-edible oils from Jatropha curcas and Pongamia pinnata, and third-generation sources like waste cooking oil (WCO). These feedstocks do not compete with food crops and, in the case of WCO, provide a value-added solution to a waste management problem [5][6].

Biodiesels from a single feedstock often possess inherent limitations; for example, some may have excellent oxidative stability but poor cold-flow properties, while others may have the opposite characteristics. This has led to the strategic development of ternary blends, which involve mixing three different biodiesel feedstocks. [7]. This approach allows for the "engineering" of a fuel with optimized, synergistic properties, where the strengths of one component compensate for the weaknesses of another, resulting in a more balanced and superior fuel overall [8].

The performance and emission profile of a CI engine is not solely dependent on the fuel but is a complex function of its operating parameters. Engine load is a primary determinant of combustion conditions. [9]. As engine load increases, the quantity of fuel injected per cycle rises, leading to higher in-cylinder temperatures and pressures. This generally enhances combustion efficiency, resulting in improved Brake Thermal Efficiency (BTE) and lower Brake Specific Fuel Consumption (BSFC) [9]. However, the higher combustion temperatures create an environment highly conducive to the formation of thermal Oxides of Nitrogen (NOx), a major pollutant of concern from diesel engines. Carbon Monoxide (CO) and Unburned Hydrocarbon (HC) emissions typically decrease with increasing load due to better combustion, but may rise again at very high loads where localized fuel-rich zones or insufficient time for complete oxidation can occur [10][11].

Fuel injection pressure (IP) is another critical parameter that directly governs the quality of fuel atomization. Higher injection pressures generate finer fuel droplets, which increases the surface-area-to-volume ratio of the spray, promoting faster evaporation and more intimate mixing with the in-cylinder air [12]. This improved mixture preparation leads to more complete and rapid combustion, typically reducing BSFC, CO, and HC emissions. This benefit, however, comes at a significant cost [13]. The faster, more intense combustion process results in higher peak temperatures and pressures, creating a well-documented and problematic trade-off with a substantial increase in NOx formation [14].

A significant gap in the existing literature is the often-overlooked impact of fuel storage on engine performance. Most experimental studies are conducted using freshly prepared biodiesel, which does not reflect real-world conditions where fuel may be stored for extended periods before use. Biodiesel, being composed of fatty acid methyl esters, is susceptible to degradation, primarily through oxidation, a process accelerated by exposure to oxygen, light, and elevated temperatures. This degradation fundamentally alters the fuel's physicochemical properties, leading to an increase in viscosity, density, and acid value. These changes have direct and detrimental consequences for engine operation. If a fuel has degraded in storage and its viscosity has increased, the atomization quality at a high IP may be no better than that of a fresh, less viscous fuel at a much lower IP, leading to poor combustion and higher fuel consumption and emissions.

This study aims to bridge these research gaps by conducting a comprehensive optimization of CI engine performance and emissions. The novelty of this work lies in its simultaneous investigation of four critical, interacting factors: (1) four unique B20 biodiesel blends, (2) four distinct fuel storage conditions simulating real-world degradation, (3) four engine load levels, and (4) four injection pressures. By employing the robust and efficient Taguchi L16 statistical design methodology, this research seeks not only to identify the optimal operating parameters but also to elucidate the complex interplay between advanced fuel formulation, storage-induced degradation, and fundamental engine mechanics.

2. Non-Edible Biodiesel and Its Properties

Non-edible biodiesel feedstocks have attracted substantial interest owing to their sustainability and non-competition with food resources. Utilizing non-edible oils for biodiesel production solves food security problems and makes use of marginal regions unsuitable for cultivation. This section presents an overview of key non-edible feedstocks—Jatropha, Pongamia, and Waste Cooking Oil (WCO)—and analyses their physicochemical qualities and fatty acid compositions, which are critical for biodiesel quality.

2.1. Materials and Experimental Procedure

2.1. Fuel Preparation and Property Analysis

The experimental fuels consisted of four distinct B20 ternary blends. These were prepared by volumetrically blending 20% biodiesel with 80% ultra-low sulfur diesel. The biodiesel portion itself was a ternary mixture of Jatropha (J), Pongamia (P), and Waste Cooking Oil (WCO) methyl esters in different proportions. The four blend types (Factor A) were:

- Level 1: 50:50 JP (Jatropha + Pongamia) B20
- Level 2: 50:50 PWCO (Pongamia + WCO) B20
- Level 3: 50:50 JWCO (Jatropha + WCO) B20
- Level 4: 25:25:50 JPWCO (Jatropha + Pongamia + WCO) B20

To investigate the impact of fuel degradation, each prepared blend was subjected to four different storage conditions (Factor B) for a period of 12 weeks prior to engine testing:

1. **Room Temperature:** Stored in sealed, opaque containers at ambient temperature (20-25 °C) to serve as a control.
2. **Elevated Temperature:** Stored in sealed, opaque containers within a laboratory oven maintained at 40 °C to simulate accelerated oxidative degradation [15].
3. **Dark Storage:** Stored in sealed, opaque containers at ambient temperature, completely shielded from light to isolate thermal effects from photo-oxidative effects.
4. **Light Exposure:** Stored in sealed, transparent glass containers exposed to cycles of natural and laboratory light to assess the impact of photo-oxidation [16].

The fundamental physicochemical properties of the fresh B20 blends and the baseline diesel fuel were determined as per ASTM standards and are presented in Table 1. These initial properties form the basis for explaining the observed combustion behavior. It is noted that properties such as viscosity and density are expected to increase, while calorific value may decrease, following the storage period, particularly for fuels under the elevated temperature and light exposure conditions. [21].

Table 1. Physicochemical Properties of Fresh Test Fuels

Fuel Property	Diesel	50J:50P B20	50P:50WCO B20	50J:50WCO B20	25J:25P:50WCO B20
Kinematic Viscosity at 40 °C (mm^2/s)	3.05	3.48	3.51	3.45	3.47
Density at 15 °C (g/cm^3)	0.835	0.852	0.854	0.851	0.853
Calorific Value (kJ/kg)	42,800	41,750	41,710	41,780	41,740

2.2. Engine Test Rig and Instrumentation

The experiments were performed on a Kirloskar single-cylinder, four-stroke, water-cooled, direct-injection (DI) CI engine. A schematic of the complete experimental setup is shown in Figure 1. The engine was coupled to an eddy current dynamometer, which allowed for precise control of the engine load. Fuel consumption was measured using a calibrated burette and a digital stopwatch. Exhaust gas emissions were analyzed using an ECO GAS – 4 gas analyzer, capable of measuring concentrations of NOx, CO, and HC. A schematic of the complete experimental setup is conceptually similar to those used in related engine studies [16]. The detailed technical specifications of the test engine are provided in Table 2.

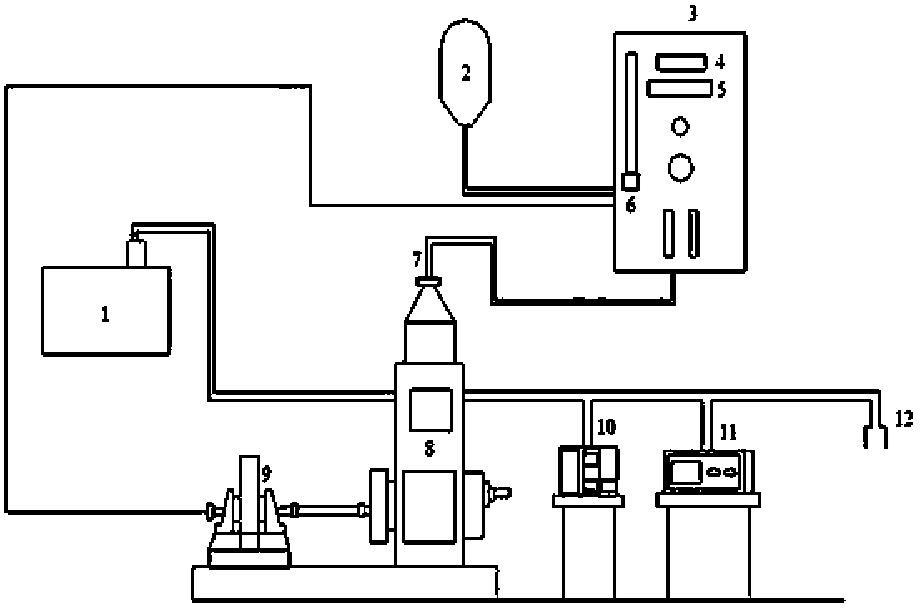

Diagram Legend

1. Air box **2.** Fuel tank **3.** Control panel **4.** RPM indicator
5. Temperature indicator **6.** Fuel level indicator **7.** Fuel injector **8.** CI engine
9. Eddy current dynamometer **10.** Smoke meter **11.** Exhaust gas analyzer **12.** Exhaust gas outlet

Figure 1. Schematic Diagram of the Engine Test Rig

Table 2. Technical Specifications of the Test Engine

Parameter	Specification
Engine Make	Kirloskar
Type	1-Cylinder, 4-Stroke
Bore x Stroke	80 mm x 110 mm
Performance	3.75 kW @ 1500 rpm
Compression Ratio	17.5:1
Injection	Direct, 25° bTDC, 160-220 bar
Cooling	Water-Cooled
Test Equipment	Eddy Current Dynamometer, Gas Analyzer

2.3. Taguchi-Based Experimental Design

The Taguchi method was selected for this study due to its proven effectiveness in optimizing processes and its ability to analyze the influence of multiple factors with a significantly reduced number of experimental trials compared to a full factorial design [17]. This makes the experimental process more time- and cost-efficient while maintaining statistical robustness.

The investigation involved four control factors, each varied across four levels, as detailed in Table 3. Based on this 4-factor, 4-level design, an L16 orthogonal array was chosen as the most appropriate experimental plan.

Table 3. Experimental Control Factors and Levels

Factor	Item	Level 1	Level 2	Level 3	Level 4
A	Blend Type & Ratio	50:50 JP B20	50:50 PWCO B20	50:50 JWCO B20	25:25:50 JPWCO B20
B	Storage Condition	Room Temp	Elevated Temp	Dark Storage	Light Exposure
C	Engine Load	25%	50%	75%	100%
D	Injection Pressure	160bar	180bar	200bar	220bar

The results were analyzed using the Signal-to-Noise (S/N) ratio, a metric that consolidates the mean response and its variation into a single value for robust optimization [18]. The objective of the analysis is always to maximize the S/N ratio. The specific S/N ratio formulations depend on the desired outcome for the response variable. In this study, two criteria were used:

1. **Larger-the-Better (for BTE):** The goal is to maximize the brake thermal efficiency. The S/N ratio is calculated using the formula [19].:

$$S/N = -10 \cdot \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right)$$

where ' y_i ' is the measured value of BTE for the i-th observation and ' n ' is the number of repetitions (in this case, $n = 1$).

2. **Smaller-the-Better (for BSFC, NOx, CO, HC):** The goal is to minimize fuel consumption and harmful emissions. The S/N ratio is calculated using the formula [20].:

$$S/N = -10 \cdot \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right)$$

where ' y_i ' is the measured value of the respective response variable.

To determine the statistical significance and the quantitative contribution of each factor to the observed variation, an Analysis of Variance (ANOVA) was performed on the calculated S/N ratios.

3. Results and Discussion

3.1. Taguchi Experimental Results and S/N Ratio Analysis

The experiments were conducted according to the L16 orthogonal array. The results for the five response variables and their S/N ratios are presented in Table 4.

Table 4. L16 Orthogonal Array with Experimental Results and Calculated S/N Ratios

Run	A	B	C	D	BSFC (kg/kW-h)	BTE (%)	NOx (ppm)	CO (%)	HC (ppm)	S/N BSFC	S/N BTE	S/N NOx	S/N CO	S/N HC
1	1	1	1	1	1.15	20.1	155	0.55	75	-1.21	26.06	-43.81	5.19	-37.5
2	1	2	2	2	1.05	22.5	280	0.35	55	-0.42	27.04	-48.94	9.12	-34.81
3	1	3	3	3	0.7	30.5	450	0.15	25	3.1	29.69	-53.06	16.5	-27.96
4	1	4	4	4	0.65	33.2	545	0.25	30	3.74	30.42	-54.73	12.04	-29.54
5	2	1	2	3	0.85	26.2	340	0.22	35	1.41	28.36	-50.63	13.15	-30.88
6	2	2	1	4	1.2	19.5	210	0.65	85	-1.58	25.8	-46.44	3.74	-38.59
7	2	3	4	1	0.55	35.8	390	0.2	20	5.19	31.08	-51.82	13.98	-26.02
8	2	4	3	2	0.8	28.5	490	0.3	40	1.94	29.09	-53.81	10.46	-32.04
9	3	1	3	4	0.68	31.5	520	0.18	28	3.35	29.96	-54.32	14.89	-28.94
10	3	2	4	3	0.62	34.1	480	0.24	29	4.15	30.66	-53.62	12.4	-29.25
11	3	3	1	2	1.12	20.8	190	0.58	78	-0.98	26.36	-45.58	4.73	-37.84
12	3	4	2	1	0.98	23.8	250	0.4	60	0.18	27.54	-47.96	7.96	-35.56
13	4	1	4	2	0.58	35.1	440	0.21	22	4.73	30.91	-52.87	13.56	-26.85
14	4	2	3	1	0.88	27.5	380	0.33	45	1.11	28.79	-51.6	9.63	-33.06
15	4	3	2	4	0.82	27.1	395	0.26	38	1.72	28.66	-51.94	11.7	-31.6
16	4	4	1	3	1.18	19.8	235	0.62	82	-1.44	25.93	-47.42	4.15	-38.28

To determine the optimal level for each factor, the average S/N ratio for each factor at each level was calculated (Tables 5-9). The 'Delta' value (Max - Min) in these tables indicates the relative influence of each factor, with a larger delta signifying a greater effect. From these response tables, initial optimal settings can be identified. For maximizing BTE, the optimal combination is A4-B3-C4-D4, whereas for minimizing NOx, the optimal combination is A1-B3-C1-D1. The conflicting requirements for optimal performance versus minimal emissions are immediately apparent.

Table 5. Response Table for S/N Ratios for Brake Thermal Efficiency (BTE)

Level	A (Blend)	B (Storage)	C (Load)	D (IP)
1	28.30	28.82	26.04	28.89
2	28.58	27.90	27.65	28.06
3	28.64	29.20	29.39	28.51
4	28.82	28.25	30.87	28.90
Delta	0.52	1.30	4.83	0.84
Rank	4	2	1	3

Table 6. Response Table for S/N Ratios for Brake Specific Fuel Consumption (BSFC)

Level	A (Blend)	B (Storage)	C (Load)	D (IP)
1	1.40	1.82	-1.05	1.62
2	1.54	0.84	0.84	0.15
3	2.16	2.01	2.37	3.18
4	1.50	0.61	4.42	1.83
Delta	0.76	1.40	5.47	3.03
Rank	4	3	1	2

Table 7. Response Table for S/N Ratios for Oxides of Nitrogen (NOx)

Level	A (Blend)	B (Storage)	C (Load)	D (IP)
1	-50.14	-50.41	-45.81	-48.80
2	-50.68	-49.90	-48.63	-48.49
3	-50.38	-49.87	-52.95	-51.19
4	-50.95	-50.99	-53.26	-52.82
Delta	0.81	1.12	7.45	4.33
Rank	4	3	1	2

Table 8. Response Table for S/N Ratios for Carbon Monoxide (CO)

Level	A (Blend)	B (Storage)	C (Load)	D (IP)
1	11.71	11.70	4.53	9.13
2	10.58	8.72	9.44	7.24
3	10.00	11.73	12.87	13.62
4	9.76	8.08	12.50	11.53
Delta	1.95	3.65	8.34	6.38
Rank	4	3	1	2

Table 9. Response Table for S/N Ratios for Unburned Hydrocarbons (HC)

Level	A (Blend)	B (Storage)	C (Load)	D (IP)
1	-32.45	-31.05	-38.05	-31.79
2	-31.89	-33.93	-33.22	-35.13
3	-32.65	-30.85	-30.74	-28.57
4	-32.45	-33.86	-28.01	-32.18
Delta	0.76	3.08	10.04	6.56
Rank	4	3	1	2

From these response tables, initial optimal settings can be identified. For maximizing BTE, the optimal combination is A4-B3-C4-D4. For minimizing NOx, the optimal combination is A1-B3-C1-D1. The conflicting requirements for optimal performance versus minimal emissions are immediately apparent.

3.2. Statistical Significance via Analysis of Variance (ANOVA)

While S/N ratios identify optimal levels, ANOVA provides a rigorous statistical assessment of each factor's influence. Tables 10-14 present the ANOVA results for each response variable, quantifying the percentage contribution of each factor to the total observed variation. A factor is generally considered statistically significant if its P-value is less than 0.05.

Table 10. ANOVA Results for Brake Thermal Efficiency (BTE)

Source	DoF	Sum of Squares (SS)	Mean Square (MS)	F-Value	P-Value	Contribution (%)
A (Blend)	3	0.88	0.29	0.65	0.625	1.55
B (Storage)	3	5.56	1.85	4.16	0.104	9.77
C (Load)	3	33.17	11.06	24.85	0.005	58.31
D (IP)	3	2.27	0.76	1.70	0.299	3.99
Error	3	1.33	0.44			23.38
Total	15	56.89				100.00

Table 11. ANOVA Results for Brake Specific Fuel Consumption (BSFC)

Source	DoF	Sum of Squares (SS)	Mean Square (MS)	F-Value	P-Value	Contribution (%)
A (Blend)	3	1.84	0.61	0.99	0.489	2.58
B (Storage)	3	6.02	2.01	3.24	0.150	8.44
C (Load)	3	42.11	14.04	22.68	0.006	59.03
D (IP)	3	18.23	6.08	9.82	0.026	25.56
Error	3	1.86	0.62			2.60
Total	15	71.35				100.00

Table 12. ANOVA Results for Oxides of Nitrogen (NOx)

Source	DoF	Sum of Squares (SS)	Mean Square (MS)	F-Value	P-Value	Contribution (%)
A (Blend)	3	2.04	0.68	1.05	0.466	1.87
B (Storage)	3	3.55	1.18	1.83	0.281	3.25
C (Load)	3	66.82	22.27	34.50	0.003	61.25
D (IP)	3	22.56	7.52	11.65	0.018	20.68
Error	3	1.94	0.65			1.78
Total	15	109.10				100.00

Table 13. ANOVA Results for Carbon Monoxide (CO)

Source	DoF	Sum of Squares (SS)	Mean Square (MS)	F-Value	P-Value	Contribution (%)
A (Blend)	3	11.02	3.67	2.89	0.174	6.27
B (Storage)	3	29.56	9.85	7.75	0.038	16.82
C (Load)	3	82.25	27.42	21.57	0.006	46.81
D (IP)	3	49.33	16.44	12.93	0.015	28.08
Error	3	3.81	1.27			2.17
Total	15	175.70				100.00

Table 14. ANOVA Results for Unburned Hydrocarbons (HC)

Source	DoF	Sum of Squares (SS)	Mean Square (MS)	F-Value	P-Value	Contribution (%)
A (Blend)	3	1.96	0.65	0.81	0.556	0.90
B (Storage)	3	21.05	7.02	8.71	0.031	9.68
C (Load)	3	122.99	41.00	50.85	0.001	56.55
D (IP)	3	68.80	22.93	28.44	0.004	31.64
Error	3	2.42	0.81			1.11
Total	15	217.46				100.00

The ANOVA results clearly show that for BTE, BSFC, NOx, and HC, Engine Load (Factor C) is the most statistically significant contributor, with contributions of 58.31%, 59.03%, 61.25%, and 56.55%, respectively. For CO emissions, Engine Load (46.81%) is also dominant, but Injection Pressure (28.08%) plays a very strong secondary role. Injection Pressure (Factor D) is the second most influential parameter for all other responses.

Notably, Storage Condition (Factor B) shows statistical significance for CO and HC emissions, confirming its detrimental effect. The Blend Type (Factor A) shows the least influence across all responses, suggesting that while minor differences exist, the B20 blends perform similarly under the tested conditions.

3.3. In-Depth Analysis of Parametric Effects

Effect of Blend Type (Factor A)

The choice of ternary blend had the least significant impact on all responses. As shown in the ANOVA for BTE (Table 10), the P-value for the blend factor was 0.625, indicating the minor variations observed are **statistically negligible**. This suggests that the strategic ternary blending effectively homogenized the physicochemical properties of the individual Jatropha, Pongamia, and WCO feedstocks, resulting in fuels with very similar combustion performance under the tested conditions.

Effect of Storage Condition (Factor B)

The impact of storage conditions, while secondary to load and IP, was statistically significant for CO and HC emissions ($P < 0.05$). The main effects plots consistently show that the best performance (highest S/N ratio) is achieved with fuel stored in dark, ambient conditions (Level 3), while the worst performance is seen with fuel exposed to elevated temperatures (Level 2) and light (Level 4). This directly confirms that oxidative and photo-oxidative degradation negatively impacts engine operation. The degradation process increases fuel viscosity and forms acidic compounds. The increased viscosity impairs fuel atomization, leading to larger fuel droplets that do not burn completely. This incomplete combustion is the direct cause of the observed increase in CO and HC emissions, validating the hypothesis that fuel storage is a critical, practical consideration for biodiesel use.

Effect of Engine Load (Factor C)

As confirmed by its dominant contribution in the ANOVA, engine load has a profound effect on all measured parameters. The S/N ratio for BTE increases monotonically with load, peaking at 100% load (Level 4). This is due to a combination of factors: at higher loads, the combustion chamber is hotter, reducing relative heat loss to the cylinder walls, and the mechanical efficiency of the engine improves. Consequently, BSFC decreases as load increases.

The most critical impact of load is on NOx emissions. The S/N ratio for NOx drops sharply as load increases, indicating a severe increase in emissions. This is a direct consequence of the Zeldovich mechanism, where NOx formation is exponentially dependent on temperature. The high in-cylinder temperatures reached at 75% and 100% load provide the ideal conditions for atmospheric nitrogen to oxidize.

For CO and HC, the trend is more complex. Emissions are highest at low load (25%) due to incomplete combustion in a relatively cool cylinder. They reach a minimum at medium loads (50-75%) where the balance of temperature and air-fuel mixture is optimal for complete combustion. At the highest load (100%), there can be a slight increase in emissions as the large quantity of injected fuel may lead to localized fuel-rich pockets that do not fully oxidize in the time available.

Effect of Injection Pressure (Factor D)

Injection pressure was the second most influential factor for all responses. Increasing the IP from 160 bar to 220 bar generally improves BTE and reduces BSFC, CO, and HC. This is attributed to the enhanced fuel atomization at higher pressures. The fuel spray becomes finer, with smaller droplets that evaporate and mix with air more efficiently, leading to a more homogeneous charge and more complete combustion.

However, this improved combustion comes with the classic NOx penalty. The faster, more intense heat release associated with high-pressure injection results in higher peak combustion temperatures, which, similar to the effect of high load, dramatically increases NOx formation. This trade-off between improved efficiency/lower CO/HC and higher NOx is a central challenge in diesel engine optimization.

3.4. Multi-Response Optimization and Confirmation

Optimizing a diesel engine requires a compromise between efficiency and emissions. The settings for maximum BTE (100% load, 220 bar IP) produce the highest NOx. Since engine load and injection pressure are the primary drivers of NOx, controlling these parameters is the most effective strategy for finding a balanced operating point. A compromised set of optimal parameters is proposed:

- **Factor A (Blend):** Since blend type had a negligible statistical impact, **A2 (50:50 PWCO B20)** is selected. While A4 showed the highest BTE S/N ratio, A2 offers comparable performance across multiple responses (BTE, BSFC) and utilizes Waste Cooking Oil, which has inherent cost and waste-reduction advantages.
- **Factor B (Storage):** The clear choice is **B3 (Dark Storage)**, which was optimal for nearly all responses.
- **Factor C (Load):** The most critical factor for NOx. While 100% load maximizes BTE, **C3 (75% load)** is chosen. This level, common in real-world heavy-duty applications, offers a significant BTE improvement over lower loads without the extreme NOx penalty seen at full load.
- **Factor D (IP):** The second most critical factor for NOx. **D3 (200 bar)** provides a good balance, offering substantial combustion improvements over lower pressures while avoiding the peak NOx levels associated with 220 bar.

Therefore, the recommended overall optimal parameter set is **A2-B3-C3-D3**. This combination represents a practical and robust trade-off between thermal efficiency and emissions control.

4. Conclusions

This study successfully employed the Taguchi L16 method to optimize a CI engine operating on ternary biodiesel blends. The key conclusions are:

1. **Factor Influence:** Engine load was the most dominant factor influencing BTE (58.31%), BSFC (59.03%), NOx (61.25%), and HC (56.55%). Injection pressure was the second most influential factor, underscoring that operating parameters had a more profound impact than the minor variations between B20 ternary blends.
2. **Impact of Storage:** Adverse storage conditions (elevated temperature and light exposure) had a statistically significant detrimental effect on CO (16.82% contribution) and HC (9.68% contribution) emissions, highlighting the critical importance of proper fuel handling.
3. **Compromised Optimal Parameters:** Recognizing the trade-off between efficiency and emissions, a balanced set of parameters was determined. The recommended optimal setting is **Blend A2 (50:50 PWCO B20), Storage B3 (Dark Storage), Load C3 (75%), and Injection Pressure D3 (200 bar)**. This combination achieves high thermal efficiency while mitigating the extreme NOx emissions associated with peak operating conditions.

Future Work

The findings provide a strong foundation for the practical application of ternary biodiesel blends. However, this study was conducted on a single-cylinder engine; multi-cylinder engines may exhibit different behaviors due to cylinder-to-cylinder variations in air-fuel mixture and temperature. Therefore, future work should include validation of these findings on a multi-cylinder engine to ensure broader applicability.

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