

Mathematical Modeling and Comparative Analysis of Noise and Vibration Characteristics of CI Engine Fueled with Biodiesel

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Abstract

As an alternative to fossil fuels, renewable energy has the potential to replace diesel in CI engines, and therefore biodiesels such as nahar, jatropa, karanja, etc. are being used as a blend with diesel in CI engines. Since biodiesel is a sustainable fuel, numerous researchers have evaluated and contrasted its performance attributes with those of diesel. The end user's comfort and level of fatigue following the usage of biodiesel blended with diesel, however, is an interesting area that requires further investigation. The current study aims to investigate the noise and vibration characteristics of unmodified and constant-speed CI engines powered by jatropa, nahar, or karanja biodiesel as a blend with diesel and also developed a mathematical model for noise and vibration responses. The vibration and sound pressure level were recorded using the FFT analyzer Brüel & Kjær Photon+ portable measuring system with RTPro software for different input parameters such as load, density, flash point, and calorific value at different levels for diesel D100 and biodiesel blends. Mathematical non-linear model was developed to predict the relationship between fuel properties and engine noise-vibration characteristics because the R square and adj. R square values of model is found to be close to each other. However, higher adj. R square value and p-value within 0.05 are the good criteria for selection of model.

Keywords: Biodiesel, vibration, noise, diesel engine, regression analysis.

1. Introduction

The use of CI engines remains popular in the transportation industry due to their high operational efficiency, fuel economy, and reliability. CI engines are a significant contributor to the generation of noise and vibrations in vehicles, which can have an impact on the durability and reliability of the machinery. Diesel engines, in particular, tend to produce elevated levels of vibration as a result of their high compression ratios and robust construction. The main reasons for the higher levels of vibration and noise in comparison to SI engines are the heterogeneous mixture and compression ignition in CI engines [1]. The vibrations can be felt throughout the vehicle, causing discomfort for passengers, and the presence of noise in the CI engine contributes to feelings of fatigue and discomfort [2]. Biodiesel, derived from plant or animal sources such as vegetable oils and animal

fats, is a renewable fuel that is currently being extensively investigated as an alternative to diesel fuel in CI engines. Blends of biodiesel are evaluated ranging from B5 (5% biodiesel) to B100 (100% biodiesel). However, the availability of biodiesel and its higher density pose significant concerns regarding its suitability as a fuel for CI engines. However, some of the benefits of biodiesels include lower emissions and the ability to be used in existing diesel engines without major modifications [3]. Additionally, many biodiesels possess higher cetane numbers and enhanced lubricity properties. Considering the upcoming stringent emission norms and the soaring prices of crude oil, biodiesel can be regarded as a more viable alternative and sustainable fuel. As a result, a significant amount of research is currently being conducted to replace diesel with biodiesel as a potential solution to address environmental concerns and reduce dependency on conventional fossil fuels. Indeed, to facilitate the transition from diesel to biodiesel, it is essential to conduct research on the vibration and noise levels of diesel engines when fueled with biodiesel. Understanding and analyzing these characteristics will help ensure a smoother and successful integration of biodiesel as a sustainable fuel alternative. Numerous studies have been conducted to investigate the noise and vibration characteristics of CI engines when biofuels are added to the fuel blend. These research efforts aim to assess the impact of using biofuels on engine performance, noise levels, and overall vibration patterns, providing valuable insights into the feasibility and potential benefits of incorporating biofuels into conventional diesel engines. Erinċ Uludamar et al. [4-5] conducted an experimental investigation on a four-cylinder diesel engine fueled with biodiesel blends derived from sunflower, canola, and corn. They assessed the vibration and sound pressure levels of the engine. The study found that engine block vibration was reduced when using biodiesel blends. Moreover, the use of diesel-biodiesel blends resulted in a significant reduction in the average sound pressure level [dB(A)] compared to using pure diesel fuel. To enhance prediction capabilities, the authors developed both linear and nonlinear regression models that demonstrated an acceptable degree of accuracy in predicting vibration and sound pressure levels. An experimental study was conducted by Ahmad Taghizadeh-Alisaraei et al. [6] to compute the noise and vibration of a six-cylinder diesel engine fueled with biodiesel. The study aimed to investigate the impact of using biodiesel on the noise and vibration characteristics of the engine. Through this research, valuable insights were gained into the behavior of the engine when running on biodiesel, providing important data for understanding its potential as a sustainable fuel option. In the study conducted by Ahmad Taghizadeh-Alisaraei et al. [6], the researchers recorded time domain and frequency signals using an FFT analyzer before and after servicing the engine. The experimental results revealed that the vibration levels increased notably at 1800 rpm and 2000 rpm. However, after the engine was serviced, the total vibration values decreased by approximately 12%. This reduction in vibration indicates the positive impact of engine maintenance on mitigating vibration levels and potentially improving the overall performance and reliability of the engine when running on biodiesel. In an experimental investigation conducted by Sarthak Nag et al. [7], a single-cylinder engine was modified to operate in dual fuel mode, with load and hydrogen percentage being varied as parameters. The study focused on assessing the impact of this modification on engine performance, particularly in terms of noise and vibration levels. The results of the study indicated a reduction in both noise and vibration, suggesting the potential benefits of using the dual fuel mode in terms of minimizing engine-generated noise and vibration, which could lead to improved comfort and reliability. In their study, Zhi Chao Ong et al. [8] analyzed the

vibration characteristics of diesel engines using *Calophyllum inophyllum* and its blends as fuel. The researchers compared the vibration levels of these biofuel blends with pure diesel and various other biofuel blends. The findings from the time domain, frequency domain, and motion visualization analyses indicated that Bio-fuel blend B20 exhibited the lowest vibration levels, as measured by the overall root mean square acceleration at full speed. This suggests that B20 blend has the potential to reduce engine vibrations, which may lead to enhanced comfort and reduced mechanical stress on the engine components. In the research conducted by Syed Javed et al. [9], the main objective was to identify the optimal fuel blend that exhibits the least vibration levels. To achieve this, the researchers investigated the vibration characteristics of several fuel blends. They utilized an Artificial Neural Network (ANN) model to predict the Root Mean Square (RMS) of velocity. The ANN predictions for RMS velocities in the horizontal, vertical, and axial directions were found to be very close to the experimental values, validating the accuracy of the model. Based on their findings, the best fuel blends with the least vibration were identified as B30 and B20, utilizing nano particle sizes of 40 nm and hydrogen flow rates of 0.5, 1.0, and 1.5 l/min. These specific fuel blends showed promising results in reducing vibration levels, indicating their potential as favorable options to minimize engine-generated vibrations and improve overall engine performance. In the research conducted by Nikhil Sharma et al. [10], the authors carried out an experimental evaluation of the noise and vibration characteristics of an engine. They correlated these characteristics with the engine's combustion behavior using a single-cylinder gasoline direct injection (GDI) research engine. During the study, two test fuels were created by blending 10% (v/v) and 20% (v/v) methanol with gasoline, designated as M10 and M20, respectively. These test fuels were then compared to a baseline gasoline fuel (G100) under various engine loads and speeds. The findings from the study revealed that the methanol-gasoline blends (M10 and M20) produced significantly higher in-cylinder pressures, heat release rates (HRRs), rates of pressure rise (RoPR), and cumulative heat releases (CHRs) when compared to the baseline gasoline (G100). These pronounced differences in combustion characteristics had a substantial impact on the engine's noise and vibration levels, indicating the influence of the methanol-gasoline blends on the engine's overall performance and noise/vibration characteristics. Tadas Žvirblis et al. [11] introduced a three-step statistical analysis algorithm, which has demonstrated enhanced prediction accuracy by incorporating vibration and sound pressure data as covariate variables in an exhaust emission prediction model. The analysis involved utilizing time domain statistics, symmetric statistical regression analysis, and ANOVA to interpret the results. By employing this approach, the researchers were able to develop a reliable and cost-effective method for assessing the effects of different alternative fuel blends on crucial parameters of diesel engines. This algorithm provides valuable insights into the impact of alternative fuels on engine performance and emissions, taking into account both vibration and sound pressure data as significant contributing factors in the prediction model. Zhaoyi Wei et al. [12] conducted a study on the transfer function and prediction of combustion noise with the aim of controlling it from the design stage. The researchers proposed a method to calculate the transfer function of combustion noise. Through experimental investigations, it was revealed that using the multiple linear regression main-injection strategy for calculating the combustion noise transfer function yielded more consistent results compared to other strategies. The findings of this research offer new insights and methods for optimizing the design of diesel engines, specifically in the context of controlling and minimizing combustion noise, which is

crucial for improving engine performance and reducing overall noise emissions. Boonthum Wongchai et al. [13] analyzed diesel engine vibration by using a hydrogen-diesel dual fuel. He developed a regression model to find the relations between hydrogen percentage and the engine vibration. The outcomes indicate that the connection between Average Peak Acceleration (APA) and hydrogen percentage (%H₂) can be anticipated using either a linear equation with an average coefficient of determination (R²) of 0.8973 or a second-degree polynomial equation with R² = 0.9592. The findings also imply that augmenting the hydrogen percentage results in a reduction of engine vibrations. Izuho Hirano et al. [14] have introduced a method for estimating the individual contributions of various engine noise components through the application of multiple regression analysis. This approach allows for a comprehensive assessment of the factors contributing to noise levels under different engine operating conditions. By utilizing the results of this multiple regression analysis, it becomes more feasible to identify specific areas for noise reduction and make informed decisions regarding noise mitigation strategies, enhancing the overall understanding of noise control in engine systems. Vaibhav R. Wakode et al. [15] conducted an investigation and developed a regression analysis model to optimize diesel engine performance with respect to variations in fuel injection pressure and compression ratio. The regression equations and optimization plots derived from this research are valuable tools for studying the effects of fuel injection pressure and compression ratio modifications on engine performance. These findings contribute to enhancing our understanding of how adjustments in these parameters can influence diesel engine operation and efficiency.

The literature highlights the necessity to investigate noise and vibration in CI engines. Jatropha, karanja, and nahar are promising biodiesel sources, and numerous studies assess their viability in CI engines, particularly at various blending ratios (B10 to B40). These studies reveal that jatropha biodiesel can be directly used without major engine modifications, delivering comparable performance to diesel while lowering emissions of particulate matter, carbon monoxide, and hydrocarbons. Although some reports mention a slight power decrease and increased fuel consumption, karanja and nahar biodiesels still show promise in reducing emissions, including nitrogen oxides for nahar [16–23]. However, research focusing on the vibration and noise levels of diesel engines using these biodiesels remains limited. Consequently, our current objective is to examine the noise and vibration characteristics of diesel engines running on blends of jatropha, karanja, and nahar biodiesels and develop a mathematical model to optimize the biodiesel blend. Indeed, one of the significant advantages of a mathematical model in the context of engine characteristics fueled with various biodiesels is its capacity to provide estimations without the need for time-consuming and expensive experimental work. This research will contribute to understanding the feasibility and benefits of using these biodiesel blends in CI engines, taking into account their effects on noise and vibration, vital factors for both engine performance and user comfort.

2. Materials And Methods

2.1. Test fuels

In this study five blends of nahar, jatropha and karanja biodiesel were prepared and used. These blends and pure diesel D100 are shown in Table 1. The biodiesel blends prepared and characterized at Indian Biodiesel Corporation, Baramati.

Table 1. Fuel properties.

Test Fuel	Density gm/cc	Flash Point °C	Calorific Value MJ/Kg	Viscosity mm ² /sec	Fire Point °C	Cetane Number	Cloud Point
D100	0.831	64.00	42.5	2.7	69	49	-6
BN10	0.8330	69.00	42.390	-	-	-	-
BN20	0.8340	75.00	42.30	2.90	88.00	49.31	1.5
BN30	0.8360	82.00	42.18	-	-	-	-
BN40	0.8390	88.00	42.09	-	-	-	-
BN50	0.8420	96.00	41.900	-	-	-	-
BJ10	0.8310	68.00	42.300	-	-	-	-
BJ20	0.8320	72.00	42.11	2.88	84.00	49.29	1.70
BJ30	0.8340	89.00	41.90	-	-	-	-
BJ40	0.8360	94.00	41.86	-	-	-	-
BJ50	0.8400	99.00	41.70	-	-	-	-
BK10	0.8320	70.00	42.40	-	-	-	-
BK20	0.8340	86.00	42.31	2.94	91	49.39	1.55
BK30	0.8370	95.00	42.16	-	-	-	-
BK40	0.8390	101.00	42.03	-	-	-	-
BK50	0.8420	107.00	41.94	-	-	-	-

2.2. Experimental engine

The single cylinder four stroke diesel engine running at constant RPM with CRDI was used during experimentation (Figure 1). The details of engine are also show in Table 2. The experimental set up comprise sensors to measure pressure, crank-angle, airflow, fuel flow, temperatures and load. The sensors are interfaced to computer through high-speed data acquisition device. A stand-alone panel box with an air box, twin fuel tanks, a manometer, a fuel measuring unit, transmitters for detecting the flow of both air and fuel, a process indicator and a piezo powering unit is part of the setup. Rotameters are used for measuring the flow of water into calorimeters and cooling engines. A programmable open ECU for diesel injection, a fuel injector, a common rail with a rail pressure sensor and pressure regulating valve, a crank position sensor, a fuel pump, and wiring are used in a CRDI diesel engine.

Table 2. Test engine specifications.

Product	CRDI VCR Engine test (Computerized)
Engine Make	Kirloskar, Single cylinder, 4 stroke, water cooled, stroke 110 mm, bore87.5 mm, 661 cc. Power 3.5 KW @ 1500 rpm, CR range 12-18

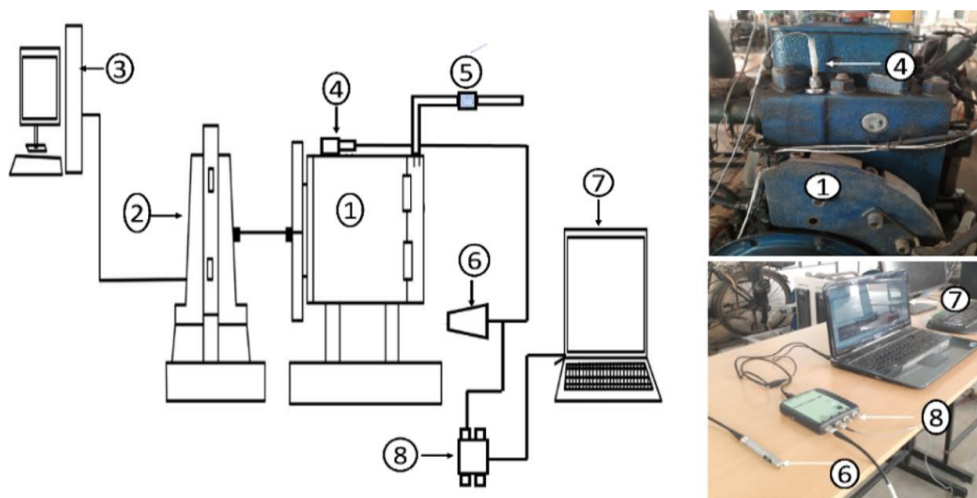


Figure 1. Experimental Setup (1. Engine 2. Dynamometer 3. Performance Measuring System 4. Accelerometer 5. Air Filter 6. Microphone 7. FFT Signal Recorder 8. FFT Channel)

2.3. Measuring system, accelerometer and microphone

The type 4514 which is piezoelectric shear accelerometers with integral electronics used to record vibration data. It has a wide frequency range, low noise-to-signal ratio and choice of sensitivity from 1 to 50 mV/ms² (10 to 500 mV/g). The transducers feature a 10-32 UNF top connector and an insulated base and are hermetically sealed. High resolution transducers provide a superior signal-to-noise ratio. The three types of accelerometers (i.e axial, radial and perpendicular) were mounted by means of a 10-32 UNF threaded stud or adhesive. Sound pressure level of the engine was measured by using a Prepolarized Free-field 1/2" Microphones Types 4188 set which has Open circuit Pressure sensitivity at 1013 hPa 23⁰C and 50% RH: -30.2 dB re 1 V/Pa or 31.1 mV/Pa, at 1000 Hz. Typically, the loaded sensitivity is 0.05 dB less sensitive than the claimed sensitivity. The random field sensitivity is the same as that of the pressure sensitivity. The free field sensitivity at 1000 Hz is 0.15 dB higher than the pressure sensitivity. The microphone was placed near to the engine block surface. RTPro software was used to record acoustic and vibration signature using a portable measuring instrument from Brüel & Kjaer

In the x (longitudinal), y (lateral), and z (vertical) axes, frequency domains were analyzed. Total vibration acceleration (a_t), which combines acceleration in the vertical (a_{ver}), lateral (a_{lat}), and longitudinal directions (a_{lon}). is determined by using following formula (1)

$$a_t = \sqrt{a_{ver}^2 + a_{lat}^2 + a_{lon}^2} \quad (1)$$

All the experiments were performed by placing the accelerometer on the engine block in longitudinal, lateral and vertical direction (figure1). The engine is constant rpm engine (1500 rpm). The readings were recorded at no load, medium load and maximum load by using diesel and fifteen biodiesel blends. The load is gradually increasing and the readings were recorded after 10 minutes when engine was stabilized. The fuel tank was drained and cleaned after using each blend.

The similar procedure is followed to record the sound pressure level. The sound pressure level (SPL) is a measure of the intensity or loudness of a sound and is typically expressed in decibels (dB). It is measured relative to a reference sound pressure level, which is usually the quietest sound that

the average human ear can hear, known as the threshold of hearing. The microphone was placed near to the engine block in perpendicular direction (*Figure 1*). The formula for calculating the sound pressure level (SPL) in a free field is [24]:

$$SPL(dB) = 20 * \log \log_{10}(P/P_{ref}) \quad (2)$$

Where SPL (dB) is the sound pressure level in decibels, P is the measured sound pressure and P_{ref} is the reference sound pressure level, which is typically set at 20 micropascals (μPa) for airborne sound in air.

2.4. Mathematical model

Prior to conducting the analysis, correlation coefficients between all relevant parameters are calculated by using XLSTAT. This crucial step allowed to determine the most appropriate input parameters for estimating the desired outputs. The input parameters are selected based on their high correlation coefficients with the predicted values. The selection of density, flash point, calorific value, and load as input parameters for estimation was driven by their significant influence on combustion characteristics, which in turn directly impact the noise and vibration levels of a compression ignition engine. These parameters were chosen due to their strong connection with engine combustion behavior, making them pivotal factors in determining the resultant noise and vibration characteristics of the engine. Regression analysis emerged as the preferred method for establishing the relationships between dependent and independent variables. This statistical technique is particularly valuable for predicting outcomes and entails identifying functional relationships between variables. In this context, it served as a powerful tool for forecasting and understanding how the selected input parameters relate to the noise and vibration characteristics of the engine.

Linear regression uses a linear equation to depict the relationship between the dependent and independent variables [5-25]. The equation is stated as:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n \quad (3)$$

Non-linear regression expresses the relationship between the dependent and independent variables as a non-linear equation [5-25]. This equation has the form:

$$Y = a_0 (X_1^{a_1}) (X_2^{a_2}) \dots (X_n^{a_n}) \quad (4)$$

Where Y represents the dependent variable, X_1, X_2, \dots, X_n represent the independent variables, β_0 is the intercept (the value of Y when all X variables are zero) and $\beta_1, \beta_2, \dots, \beta_n$ are the coefficients or weights associated with each independent variable, representing the change in Y for a one-unit change in the corresponding X variable and $a_0, a_1, a_2, \dots, a_n$ are equation parameters

3. RESULTS AND DISCUSSION

3.1. Vibration of the engine

Experimental data were collected at engine block by using B&K RT Photon+ FFT analyser. Frequency domain signals acquired for vibration acceleration at constant 1500 rpm with no load, medium load and high load respectively. Throughout this work, the engine was fuelled with sixteen different fuels (D100, BN10, BN20, BN30, BN40, BN50, BJ10, BJ20, BJ30, BJ40, BJ50, BK10,

BK20, BK30, BK40 and BK50). Biodiesel fuels were added up to 50% by volume into pure diesel. Fuel properties of diesel and biodiesel (EN590 and EN14214 respectively) were presented in Table 1. The study's goal is to identify the ideal fuel blend by investigating the vibrational behaviour of various fuel blends. According to the study as shown in figures 2-4 engine load had a substantial impact on engine vibration and noise.

Figure 2 depicts the vibration acceleration versus engine load graph of nahar, jatropha and karanja biodiesel and is compared with the pure diesel at no load, medium load and maximum load respectively. For nahar biodiesel it indicates that at no load and medium load, the vibration acceleration is decreased by 2.54% to 11.85% for all nahar biodiesel blend. Whereas at maximum load it is reduced by 12.67% to 19.97% for BN10 and BN20, when compared with diesel. For jatropha biodiesel, it indicates that at no load the vibration acceleration decreased, up to 40% biodiesel blending, by 17.15% to 27.53% whereas at medium load the vibration acceleration decreased for BJ10 and BJ30 by 16.62% to 17.26%. The vibration acceleration at maximum load is less for all the blends of jatropha, except BJ40, by 0.04% to 5.30%. The results of karanja biodiesel shows that the vibration acceleration is decreased by 0.29% to 28.13% at no load for karanja biodiesel blend BK10 and BK20. Also, at medium and maximum load the vibration acceleration is decreased by 6.34% to 31.43% for BK10, BK20 and BK30, compared with pure diesel.

Because engine vibrations are significantly affected by changes in the engine load, observed acceleration was highest at high loads and lowest at no load. All 15 blends showed the same pattern. The results of the analysis are presented in figure 3 and figure 4, which provide a visual comparison of acceleration versus load for various fuel blends and acceleration versus different fuel blends at varying loads. According to the results, with no load, vibration acceleration is reduced for several biodiesel blends, including BN10, BN20, BN30, BN40, BN50, BJ10, BJ20, BJ30, BK10, and BK20 when compared to D100 (pure diesel) and the average reduction in vibration acceleration ranges from 0.29% to 28.13% compared to D100. At medium load, vibration acceleration is decreased for biodiesel blends BN10, BN20, BN30, BN40, BN50, BJ10, BJ30, BK10, BK20, and BK30 when compared to D100 and the average reduction in vibration acceleration varies from 0.49% to 31.80% compared to D100. While for high load, vibration acceleration is reduced for biodiesel blends BN10, BN20, BJ10, BJ20, BJ30, BJ50, BK10, BK20, and BK30 compared to D100. The average reduction in vibration acceleration ranges from 0.49% to 31.80% compared to D100. This reduction in vibration acceleration is attributed to the increased oxygen content in biodiesels, which results in more efficient and higher-quality combustion. These findings suggest that using biodiesel blends can have a positive impact on reducing vibration levels in the engine, especially under certain load conditions [1-3].

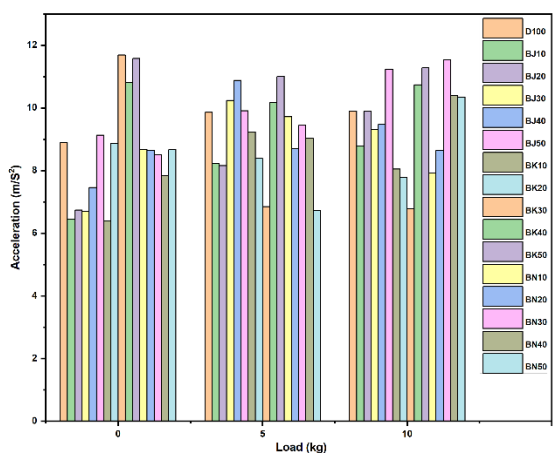


Figure 2. Acceleration versus load when the engine fuelled with nahar, jatropha and karanja biodiesel.

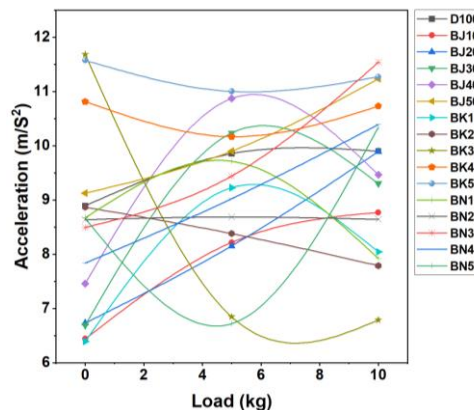


Figure 3. Comparison of acceleration versus load for all fuel blend.

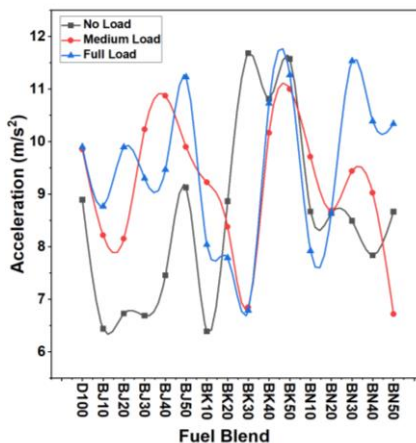


Figure 4. Comparison of acceleration versus all fuel blend at different load.

3.2. Sound pressure level of the engine

Due to the different dynamic stresses that compression ignition engines exert on structures with varying stiffness, damping, and response characteristics, these engines are particularly complicated systems from an acoustic perspective. In order to process the results, a weighted sound pressure level that is similar to how the human ear perceives sound was used. The results of noise measurements using diesel and biodiesel blend fuels are displayed in Figures 5–7.

Figure 5 illustrates the recorded sound pressure levels for various nahar, jatropha and karanja biodiesel blends and pure diesel under different load conditions, namely, no load, medium load, and maximum load. The findings indicate that, for nahar biodiesel, when compared to pure diesel, only BN20 blend experiences a 0.15% increase in sound pressure level at medium load. Conversely, the remaining nahar biodiesel blends exhibit a maximum decrease of 1.92% in sound pressure level. The results of jatropha biodiesel demonstrate that, at maximum load, the sound pressure level increased by 0.11% for BJ40 and 0.61% for BJ50 when compared to pure diesel. Conversely, the remaining biodiesel blends exhibited a maximum decrease of 1.01% in sound pressure level. The data of

karanja biodiesel reveals that, at both no load and maximum load, BK10, BK20, and BK30 experienced a maximum decrease in sound pressure level of 0.93%. At medium load, the decrease in sound pressure level ranges from BK10 to BK40, with a reduction of 0.52%. On the other hand, other karanja biodiesel blends showed a maximum increase in sound pressure level of 0.56%.

The results of sound pressure levels are presented in figure 6 and figure 7. For the biodiesel blends BN10, BN20, BN30, BN40, BN50, BJ10, BJ20, BJ30, BK10, BK20, and BK30, the recorded Sound Pressure Level is somewhat reduced with no load by 0.33%, 0.63%, 0.62%, 1.08%, 1.27%, 0.11%, 0.61%, 0.15%, 0.71%, 0.76%, and 0.32%, respectively. At medium load, Sound Pressure Level is decreased for biodiesel blends BN10, BN30, BN40, BN50, BJ10, BJ20, BJ30, BJ40, BJ50, BK10, BK20, BK30 and BK40 by 0.41%, 1.57%, 1.16%, 1.92%, 0.70%, 0.97%, 1.01%, 0.32%, 0.67%, 0.35%, 0.52%, 0.02% and 0.05% respectively. BN10, BN20, BN30, BN40, BN50, BJ10, BJ20, BJ30, BK10, BK20, and BK30 biodiesel blends all have sound pressure levels that are reduced for high load by 0.14%, 0.98%, 0.84%, 1.70%, 1.74%, 0.13%, 0.57%, 0.14%, 0.53%, 0.93%, and 0.24%, respectively. Engine vibration may be associated to lower sound pressure level.

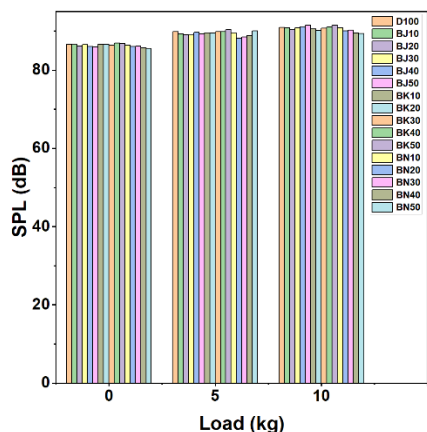


Figure 5. Sound pressure level versus load when the engine fuelled with nahar, jatropa and karanja biodiesel.

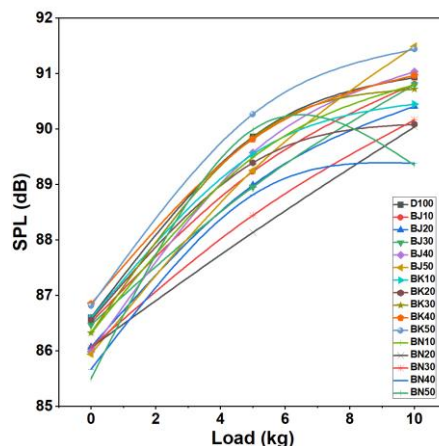


Figure 6. Comparison of Sound pressure level versus load for all fuel blend.

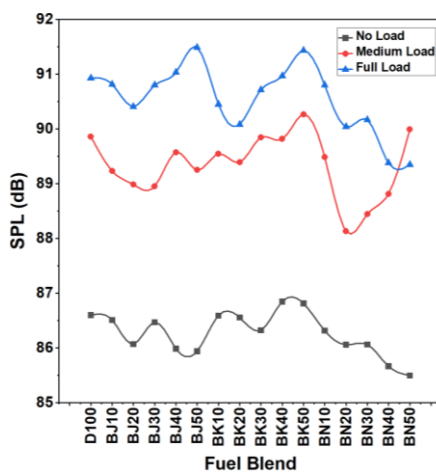


Figure7. Comparison of Sound pressure level versus all fuel blend at different load.

3.3 Model of non-linear regression analysis

Regression analysis is a fundamental and widely used statistical methodology for quantifying the relationship between a response variable (dependent variable) and one or more predictor variables (independent variables). In this study non-linear regression analyses are employed to examine experimental data. The objective of work is to forecast two vital parameters of the internal combustion engine: vibration and sound pressure levels. To make these predictions, specific input parameters, including density, flash point, calorific value and load as a categorical variable is selected. For the regression analyses, a popular software package STATA is used for statistical analysis, data management and data visualization. The outcomes of this analysis are presented in the following equations, which provide valuable insights into the relationships between the selected input parameters and the vibration and sound pressure levels of the engine.

$$\ln Vibration = -136.03 + 35.69 * \ln CV - 2.5382 * \ln D + 0.8681 * \ln FP + L(-0.0649 \text{ if Medium Load}, -0.06428 \text{ if No Load}) \tag{5}$$

$$\ln Noise \text{ dB} = -1.4347 + 1.5429 * \ln CV + 0.1678 * \ln D + 0.045 * \ln FP + L(-0.0106 \text{ if Medium Load}, -0.046 \text{ if No Load}) \tag{6}$$

Where CV is calorific value, D is density, FP is flash point and L is load.

Equations (5) and (6) employ non-linear calculations to estimate the vibration and sound pressure levels of the engine when input parameters are substituted into the equations. In evaluating the performance of these models, correlation coefficient (R) and mean absolute percentage error (MAPE) is considered as key performance parameters. The results of this evaluation are presented in Table 3.

Table 3. Statistical comparison non-linear regression models.

		R- Square	Adj R-Square	MAPE	p-value
Vibration	Non - Linear	0.7542	0.6176	1.966271	0.0134
Noise	Non - Linear	0.9662	0.9475	0.063572	0.0000

It can be concluded that non-linear regression methods reasonably provide accurate predictions of vibration and sound pressure levels with acceptable levels of accuracy.

4. Conclusions

The study attempted to determine the effect of biodiesel fuels on the noise and vibration characteristics of a constant rpm unmodified diesel engine. Throughout the experiments, the engine was powered by nahar, jatropa, and karanja biodiesel fuels. Furthermore, non-linear regression model used on experimental data to estimate engine vibration and sound pressure levels. Based on the observations, the following conclusions are formed.

- Engine load greatly impacts on engine vibration and sound pressure levels. At a higher load with a pure diesel, vibration increased by 10.17% as compared to no load. However, the sound pressure level increased by 4.76%.
- Compared to pure diesel, the use of biodiesel blends from nahar, jatropa, and karanja leads to a reduction in engine vibrations and sound pressure levels across various loads. Specifically, for

nahar biodiesel, the maximum reductions in vibrations and sound pressure levels are 31.80% and 1.92%, respectively, at low and medium loads. For jatropha biodiesel, these reductions are observed at all loads, with maximum decreases of 27.55% and 0.97%, respectively. Similarly, for karanja biodiesel, the maximum reductions at all loads are 28.13% and 0.93%, respectively.

- The objective of this work is to develop the non-linear regression model. Nonlinear regression model can be used to forecast vibration and sound pressure levels with an acceptable degree of accuracy.
- Of the biodiesels listed above, Nahar biodiesel exhibits superior resilience to vibration and sound pressure level.

Other biodiesels with different percentage of blends with diesel can be assessed and compared with the aforementioned biodiesels for vibration and noise characteristics along with performance attributes.

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