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Impact of Various Biodiesel and Partially Hydrogenated Biodiesel Mixtures on Torque, Power, and Specific Fuel Consumption: An Experimental Study With Mathematical Modeling

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ABSTRACT - The widespread reliance on diesel fuel for transportation and industrial applications is causing environmental pollution, showing the need to explore better alternatives. In this context, the use of biodiesel, or in combination with partially hydrogenated biodiesel, presents a potential substitute for conventional diesel fuel. Therefore, this research aimed to investigate the effects of incorporating biodiesel or partially hydrogenated biodiesel into diesel fuel on torque, power, and Specific Fuel Consumption (SFC). The experiments were carried out by incorporating seven mixtures of diesel fuel, varying from 100% to 70%. The results showed that both biodiesel and partially hydrogenated biodiesel improved power, torque, and SFC compared to conventional diesel fuel, across various ratios and engine rotation. The optimal performance of these mixtures was achieved at approximately 2000 rpm (rotation per minute). Additionally, mathematical models were developed to predict torque and power. The models were optimized for use at engine speeds of 2000 rpm and 4000 rpm, with biodiesel concentrations ranging from 10% to 30% in fuel mixture.

Keywords: biodiesel, partial hydrogenated biodiesel, torque, power, specific fuel consumption.

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INTRODUCTION

The use of diesel fuel is dominated by the transportation and industrial sectors on a large scale. This phenomenon causes environmental pollution due to the combustion process of diesel fuel, which produces gas in the form of black smoke (ten Brink et al. 2022) and nitrogen oxides (NO) (Sittichompoo et al. 2022). The negative impact of environmental pollution includes the depletion of the ozone layer, which plays a significant role in maintaining the stability of the Earth's temperature (Liu et al. 2022). Regarding health, smoke generated from diesel combustion can trigger respiratory diseases and lung cancer (Konur 2021). Several investigations have been conducted to explore more environmentally friendly and less harmful diesel fuel alternatives with similar characteristics and uses. Among these alternatives, biodiesel is considered a more environmentally friendly option without negative impacts (Kaya & Kökkülünk 2023). Moreover, using biodiesel helps to preserve national energy sustainability by lowering reliance on fossil fuels (Supriyanto & Rani 2023).

Biodiesel can be produced from various sources such as vegetable oil (Tshizanga et al. 2017), animal fat (Öğüt et al. 2022; Encinar et al. 2021), and algae (Elkelawy et al. 2021). However, using food sources cause imbalances and increase the cost of raw materials, showing the need for other alternatives. Non-food raw materials for biodiesel production include castor oil (Jatropha curcas) (Chaudhary et al. 2019; Singh et al. 2021), rubber seeds (Paul et al. 2021), tobacco seeds (Rajan et al. 2021), kapok seeds (Pooja et al. 2021; Udhayakumar et al. 2021), coconut oil (Wirawan et.al 2013), palm oil (Arina & Nasikin 2022), and waste cooking oil (Mansir et al. 2018). Waste cooking oil, which is generated from households, is specifically suitable as biodiesel.

The characteristics of waste cooking oil biodiesel meet Indonesian National Standard (SNI) for biodiesel fuel in the country. These include kinematic viscosity, density, flash point, sulfur content, pour point, residual carbon, heating value, water content, and acid number (Zainudin et al. 2020). However, the oxidation stability is still lower compared to diesel fuel due to the presence of unsaturated bonds, namely methyl esters (Aisyah et al. 2016). These include single bonds (mono-unsaturated esters) such as oleic acid and double bonds (poly-unsaturated esters), namely linoleic and linolenic acids (Wei et al. 2018). The oxidation process, caused by the presence of air in fuel, produces acids and solids or polymers. Acid content can corrode fuel lines and tanks, while solids or polymers clog nozzles and fuel filters. To address this issue, adding antioxidants or partial hydrogenation is essential.

Partial hydrogenation of biodiesel is an effective method to increase oxidation stability by breaking double bonds (Adu-Mensah et al. 2019). Key variables influencing this process include temperature, stirring, amount of catalyst, selection of catalyst, hydrogen, and raw material quality (Wongjaikham et al. 2021). Therefore, partial hydrogenation is expected to optimize biodiesel use and engine performance (Kanth & Debbarma 2021).

Based on the description, this study aimed to determine torque, power, and Specific Fuel Consumption (SFC) as parameters for diesel engines using various types of fuel mixture. A total of seven types of fuel were tested, including diesel fuel, as well as a mixture of diesel fuel with biodiesel, and partially hydrogenated biodiesel. Biodiesel for this research was obtained from waste cooking oil. After experiment, mathematical equations were developed for each parameter of various fuel mixtures to observe the relationships between fuel mixtures and torque, power, as well as SFC.

METHODOLOGY

Materials

Materials used in this research vary from fully diesel fuel to mixtures of diesel and biodiesel, as well as partially hydrogenated biodiesel. As stated previously, biodiesel from waste cooking oil is used for the experiment. Table 1 shows the complete materials, with each fuel in the experiment using a volume of 1000 ml.

Table 1
Used materials for the research

Main fuel	Additional fuel	Fuel Code
Diesel Fuel (100%)	-	D100
Diesel Fuel (90%)	Biodiesel (10%)	B10
Diesel Fuel (80%)	Biodiesel (20%)	B20
Diesel Fuel (70%)	Biodiesel (30%)	B30
Diesel Fuel (90%)	Partially Hydrogenated Biodiesel (10%)	D90PH10
Diesel Fuel (80%)	Partially Hydrogenated Biodiesel (20%)	D80PH20
Diesel Fuel (70%)	Partially Hydrogenated Biodiesel (30%)	D70PH30

To obtain the partially hydrogenated biodiesel as fuel, several materials were prepared as shown in Table 2, with the measurement expressed as gram in ratio. When a larger fuel quantity is required, the measurement can be multiplied by two.

Table 2
Materials to create partially hydrogenated

Materials	Measurement
Biodiesel	350.0g
Aquades	180.0g
Aluminum oxide	17.5g
Isopropyl alcohol	180.0g

Several tools are also prepared in this research to aid the conducted experiments, as shown in Table 3.

Table 3
Tools for the research

Tools	Detail
Diesel fuel and biodiesel	To act as material. The details are mentioned in Table 1.
Diesel Vehicle	To act as test equipment. Used vehicle: Isuzu Panther (4JA1L Turbocharger, 2.499 cc, 80 PS @ 3.500 rpm, 192 Nm @ 1.800 rpm)
Chassis Dynamometer	To measure the amount of power and torque in an engine without removing or separating from the vehicle.
Stopwatch	To measure the elapsed time for each experiment.
Thermometer	To measure the temperature in making partially hydrogenated biodiesel.
Magnetic stirrer	To stir the mixture when making the partially hydrogenated biodiesel.
Glass beaker	To put the partially hydrogenated biodiesel during preparation.
Hose and measuring cup	To flow and calculate the amount of used materials.

METHODOLOGY

Partially hydrogenated biodiesel was prepared before starting the experiment using the following process: 1). All materials as shown in Table 2 and tools were prepared for making partially hydrogenated biodiesel. The tools used were a thermometer, magnetic stirrer, and measuring cup; 2). All materials were placed in a beaker and measurement was in ratio; 3). The beaker was put in a magnetic stirrer, and set to rotate at 500 rpm (rotation per minute) at 900C temperature for 90 minutes; 4). The mixtures were removed and partially hydrogenated biodiesel was ready to use for the experiment.

This research used an experimental method using a chassis dynamometer to assess the performance of diesel engine. The process included the following steps: 1). The test equipment was prepared and positioned in a safe place; 2). A hose and a measuring cup were prepared to calculate the amount of fuel used by the by-pass method from fuel tank; 3). Diesel vehicle engine was started initially to warm up without a load (idle) for approximately 10 minutes. This process was performed to ensure the engine would work at normal temperatures; 4). The vehicle was raised on the chassis dynamometer; 5). The front wheel of diesel vehicle was positioned on the roller and the rear wheel was on the rear dynamometer; 6). The right and left sides of the vehicle were tied with belts on the front and rear wheels. This was performed for the vehicle to balance and increase the grip of the tires on the rollers as well as safety during testing; 7). A stopwatch was used to measure the time out of fuel consumption when the engine was running; 8). The engine was started and set to the 4th gear position (the most optimal condition in producing engine performance); 9). The engine was tested to obtain torque and power with the spontaneous throttle rotation method; 10). The gas pedal of diesel vehicle was pressed until the engine speed reached the desired speed. The results obtained were directly recorded on the computer device used for testing; 11). Fuel consumption and the time taken to spend fuel were observed and recorded; 12). The mathematical model was attempted to determine the impact of fuel mixture on torque, power, and SFC.

These processes were repeated respectively for each mixture. The first experiment was for D100, followed by B10, B20, B30, D90PH10, D80PH20, and D70PH30.

RESULT AND DISCUSSION

Experiment for Torque

Combustion of fuel in diesel engine produces energy. This process starts with the movement of the piston from the top dead center (TDC) to the bottom dead center (BDC), where air enters through the inlet valve and the outlet valve is closed. Furthermore, the air is compressed through the movement of the piston from BDC to TDC, where the inlet and outlet valves are closed. At a few degrees before the piston reaches TDC, the air has high pressure and temperature, which allows the spraying of fuel for the combustion process to occur. This combustion produces an indication pressure that will push the piston to move from TDC to BDC, with both outlet and inlet valves remaining closed. The thrust movement that occurs between the piston and the crankshaft will produce rotational motion or torque from the acceleration to support the performance of diesel engine.

By using chassis dynamometer, the highest value for torque testing in D100 is obtained with rotation of 1900 rpm, producing a torque of 104.78 ft.lbs. For diesel with mixture, the optimum torque is obtained when the speed of rotation is approximately 2000 rpm, with B20 yielding 2100 rpm. The impact of fuel mixtures on torque in the experiment is shown in Table 4.

Table 4
Experiment result for the impact on torque

Speed (rpm)	Resulted Torque (ft.lbs)						
	D100	B10	B20	B30	D90 PH10	D80 PH20	D70 PH30
1700	96.75	53.75	41.87	11.81	64.05	26.20	13.78
1800	103.94	68.62	81.10	65.26	83.49	28.91	53.58
1900	**104.78**	93.93	101.92	87.99	101.55	69.13	83.67
2000	104.18	105.79	108.75	102.96	**106.37**	92.30	101.23
2100	103.32	**107.67**	**108.58**	**106.42**	105.77	101.76	**105.45**
2200	101.84	105.97	106.98	105.38	104.67	**102.46**	104.22
2300	99.82	103.87	105.33	103.68	103.58	100.74	102.44
2400	97.54	101.57	103.26	101.85	101.98	98.84	100.77
2500	95.24	99.01	100.98	99.86	99.99	96.75	99.00
2600	92.91	96.49	98.65	97.88	97.88	94.82	97.14
2700	90.46	94.21	96.37	95.93	95.77	93.00	95.25
2800	87.89	92.03	94.11	93.82	93.52	90.93	93.27
2900	85.38	89.49	91.70	91.46	91.08	88.50	91.01
3000	82.97	86.60	89.10	88.89	88.65	85.95	88.51
3100	80.23	83.74	86.46	86.03	86.36	83.56	85.99
3200	77.37	81.14	83.81	83.06	84.10	81.25	83.45
3300	74.95	78.68	81.08	80.38	81.64	78.77	80.87
3400	72.34	76.23	78.23	77.65	78.87	75.99	78.12
3500	69.35	73.38	74.99	74.39	75.96	73.04	75.01
3600	66.41	69.68	71.19	71.10	72.90	69.91	71.89
3700	62.98	65.62	67.51	68.09	69.72	66.40	68.95
3800	59.51	62.09	64.18	64.99	66.38	62.65	65.65
3900	56.10	59.35	61.01	61.80	63.00	59.32	62.36
4000	52.71	56.02	57.70	58.36	59.64	56.17	58.91
4100	49.24	51.93	53.78	54.57	55.61	52.54	54.76
4200	45.06	46.60	49.45	50.79	51.25	48.26	50.52

B20 comprising 20% biodiesel and 80% diesel at 2100 rpm produced the best torque in the experiment. This mixture mostly outperformed others in terms of torque, although the performance decreases when rotation is below 2000 rpm or above 3000 rpm. This showed that for 2000 to 3000 rpm, B20 yields the highest torque, but there is no significant difference between mixtures. As shown in Table 4, 2100 rpm was the speed of rotation to reach the most optimum torque for most mixtures. This suggested that yielded torque was directly proportional to rotation speed. However, a continuous decrease was observed when more rotation was added after the optimum rotation for every mixture, as shown in Figure 1.

Figure 1
Relation between rotation speed and mixture to produce torque

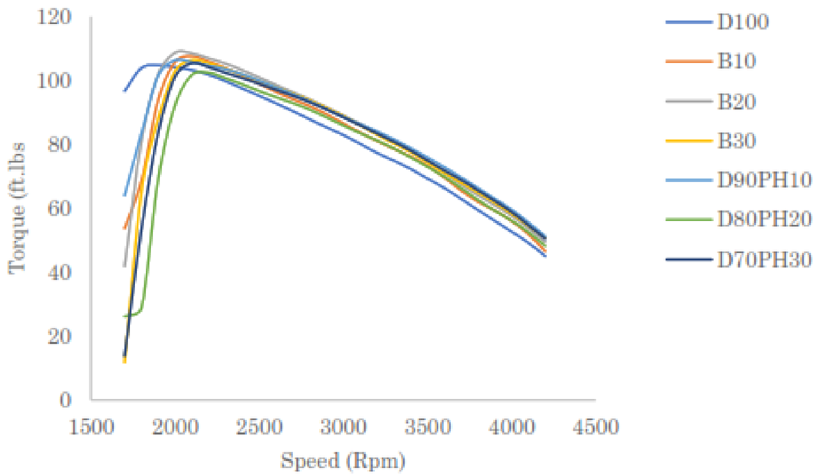

Table 5
Experiment result for the impact on power

Speed (rpm)	Resulted Power (HP)						
	D100	B10	B20	B30	D90 PH10	D80 PH20	D70 PH30
1700	31.31	17.40	13.55	3.82	20.73	8.48	4.46
1800	35.62	23.52	27.79	22.37	28.61	9.91	18.36
1900	37.91	33.98	36.87	31.83	36.73	25.01	30.27
2000	39.67	40.28	41.41	39.21	40.51	35.15	38.55
2100	41.31	43.05	43.42	42.55	42.29	40.69	42.16
2200	42.66	44.39	44.81	44.14	43.85	42.92	43.66
2300	43.71	45.49	46.12	45.40	45.36	44.12	44.86
2400	44.57	46.41	47.19	46.54	46.6	45.17	46.05
2500	45.33	47.13	48.07	47.53	47.6	46.05	47.12
2600	46.00	47.77	48.83	48.45	48.46	46.94	48.09
2700	46.50	48.43	49.54	49.32	49.23	47.81	48.97
2800	46.86	49.06	50.17	50.02	49.86	48.48	49.73
2900	47.15	49.41	50.63	50.50	50.29	48.87	50.25
3000	**47.39**	**49.47**	50.90	50.77	50.64	49.10	50.56
3100	47.36	49.43	51.03	**50.78**	50.97	49.32	50.76

Table 5 (continued)
Experiment result for the impact on power

Speed (rpm)	Resulted Power (HP)						
	D100	B10	B20	B30	D90 PH10	D80 PH20	D70 PH30
3200	47.14	49.44	**51.06**	50.61	51.24	**49.51**	**50.85**
3300	47.09	49.44	50.94	50.50	**51.30**	49.49	50.81
3400	46.83	49.35	50.64	50.27	51.06	49.20	50.57
3500	46.22	48.90	49.97	49.57	50.62	48.67	49.98
3600	45.52	47.76	48.80	48.73	49.97	47.92	49.28
3700	44.37	46.23	47.56	47.97	49.12	46.78	48.57
3800	43.06	44.92	46.44	47.02	48.03	45.33	47.50
3900	41.66	44.07	45.30	45.89	46.78	44.05	46.31
4000	40.14	42.67	43.95	44.45	45.42	42.78	44.87
4100	38.44	40.54	41.98	42.60	43.41	41.01	42.75
4200	36.04	37.27	39.54	40.61	40.99	38.59	40.40

Although biodiesel improved the overall torque, the experiment showed that there was a slight difference between mixtures and diesel (D100) in torque. (Kaya & Kökkülünk 2023) reported that biodiesel did not significantly improve torque of the engine.

Experiment for Power

Power shows the amount of work divided by the duration of a single diesel cycle. It is produced by multiplying the volume of the piston stroke per unit time in a single cycle by the combustion pressure or the average indicator pressure. To overcome the friction between the shaft and bearing as well as the piston and cylinder wall, diesel engine needs power indication. Furthermore, several accessories including a lubrication pump, cooling water pump, air intake valve movement, and exhaust gas outlet mechanism, must be driven by power indication.

By using a chassis dynamometer, the maximum power measurement in D100 was achieved at 3000 rpm, obtaining power of 47.39 horsepower (HP). When diesel engine was running at a speed of approximately ±3000 rpm with a mixture, the best HP was produced at 3300 rpm for B20. Table 5 provides specifics on how different fuel mixtures affected power in this research.

Table 5
Experiment result for the impact on power

Speed (rpm)	Resulted Power (HP)						
	D100	B10	B20	B30	D90 PH10	D80 PH20	D70 PH30
1700	31.31	17.40	13.55	3.82	20.73	8.48	4.46
1800	35.62	23.52	27.79	22.37	28.61	9.91	18.36
1900	37.91	33.98	36.87	31.83	36.73	25.01	30.27
2000	39.67	40.28	41.41	39.21	40.51	35.15	38.55
2100	41.31	43.05	43.42	42.55	42.29	40.69	42.16
2200	42.66	44.39	44.81	44.14	43.85	42.92	43.66
2300	43.71	45.49	46.12	45.40	45.36	44.12	44.86

Table 5 (continued)
Experiment result for the impact on power

Speed (rpm)	Resulted Power (HP)						
	D100	**B10**	**B20**	**B30**	**D90 PH10**	**D80 PH20**	**D70 PH30**
2400	44.57	46.41	47.19	46.54	46.6	45.17	46.05
2500	45.33	47.13	48.07	47.53	47.6	46.05	47.12
2600	46.00	47.77	48.83	48.45	48.46	46.94	48.09
2700	46.50	48.43	49.54	49.32	49.23	47.81	48.97
2800	46.86	49.06	50.17	50.02	49.86	48.48	49.73
2900	47.15	49.41	50.63	50.50	50.29	48.87	50.25
3000	**47.39**	**49.47**	50.90	50.77	50.64	49.10	50.56
3100	47.36	49.43	51.03	**50.78**	50.97	49.32	50.76
3200	47.14	49.44	**51.06**	50.61	51.24	**49.51**	**50.85**
3300	47.09	49.44	50.94	50.50	**51.30**	49.49	50.81
3400	46.83	49.35	50.64	50.27	51.06	49.20	50.57
3500	46.22	48.90	49.97	49.57	50.62	48.67	49.98
3600	45.52	47.76	48.80	48.73	49.97	47.92	49.28
3700	44.37	46.23	47.56	47.97	49.12	46.78	48.57
3800	43.06	44.92	46.44	47.02	48.03	45.33	47.50
3900	41.66	44.07	45.30	45.89	46.78	44.05	46.31
4000	40.14	42.67	43.95	44.45	45.42	42.78	44.87
4100	38.44	40.54	41.98	42.60	43.41	41.01	42.75
4200	36.04	37.27	39.54	40.61	40.99	38.59	40.40

As shown in Table 5, the most HP was obtained when D90PH10 was applied as a mixture. However, B20 still had significant results in power in line with the previous subsection of torque, where B20 80% diesel and 20% biodiesel showed exceptional performance in power and torque. The difference between the experiment for torque and power was the most optimum rotation. The results showed that the optimum rotation was approximately 2000 rpm but 3000 rpm had the best performance.

Figure 2 shows that the 'elbow' of the line charts occurs at approximately 2000 rpm. Powers above 2000 rpm are only slightly increased, followed by a gradual decrease in higher speed. Therefore, the most HP was obtained at 3000 rpm, and optimum power was started at 2000 rpm. (Öğüt et al. 2022) reported that the addition of biodiesel in the mixture increased power at 2000 rpm, showing maximum performance.

Specific Fuel Consumption

The quantity of fuel an engine uses to generate power per unit of time is called SFC. Initially, the formula is used to calculate SFC, as expressed in Equation 1.

$$SFC = \frac{m_f}{P} \tag{1}$$

In Equation 1, mf shows the mass flow rate of fuel in kg/hour, and P indicates power measure in HP. Equation 2 clarifies the calculation of m_f

$$m_f = \frac{sgf.V_y.10^{-3}}{t_f}.3600 \tag{2}$$

where:
sgf = specific gravity (gr/ml)
Vy = volume of fuel (ml)
tf = the time taken to run out of fuel (sec)

In this experiment, the specific gravity for all fuel mixtures is precalculated (Ala'a et al. 2024). Table 4 shows the specific gravity for each non-mixed fuel. Meanwhile, Table 6 shows the specific gravity for fuel mixtures in this research.

Table 6
Specific gravity for individual fuel

Fuel Type	Specific Gravity
Diesel Fuel	0.8500 gr/ml
Biodiesel	0.8624 gr/ml
Partial Hydrogenated Biodiesel	0.8453 gr/ml

Specific gravity for each mixture using precalculated values based on the composition of the mixtures, as shown in Table 7.

Table 7
Specific gravity for each fuel mixtures

Fuel Code	Specific Gravity
D100	0.850 gr/ml
B10	0.850×90% + 0.8634×10% = 0.853 gr/ml
B20	0.850×80% + 0.8634×20% = 0.854 gr/ml
B30	0.850×70% + 0.8634×30% = 0.855 gr/ml
D90PH10	0.850×90% + 0.8453×10% = 0.851 gr/ml
D80PH20	0.850×80% + 0.8453×20% = 0.850 gr/ml
D70PH30	0.850×70% + 0.8453×30% = 0.849 gr/ml

Mass flow rate can be calculated based on Equation 2 when specific gravity of mixtures and the time taken to run out of fuel are known. Using stopwatch, the time taken is recorded in Table 8 including mass flow rate.

Table 8
Mass flow rate for each fuel mixture

Fuel Code	Time taken to run out	Mass flow rate (gr/ml)	Mass flow rate (kg/h)
D100	576 sec	1.479	5.325
B10	541 sec	1.576	5.676
B20	602 sec	1.418	5.106
B30	515 sec	1.661	5.981
D90PH10	390 sec	2.179	7.846
D80PH20	900 sec	0.945	3.401
D70PH30	828 sec	1.025	3.691

After obtaining mass flow rate, SFC for each rotation speed and mixture was calculated using Equation 1, with power from Table 5. The results obtained were shown in Table 9, where the application of B30 produced the optimum SFC at 3000 rpm. Moreover, approximately all mixtures produced the best result at a value above 3000 rpm. Similar to power experiment, the optimal SFC started at 2000 rpm, which corresponded to the inflection point of the curve, as shown in Figure 3. This is significantly apparent because power is used for calculation in SFC as in Equation 1.

Table 9
Experiment result for the impact on SFC

Speed (rpm)	Resulted SFC						
	D100	B10	B20	B30	D90 PH10	D80 PH20	D70 PH30
1700	0.2005	0.3236	0.2886	0.2039	0.2393	1.0617	0.2696
1800	0.1884	0.224	0.2175	0.1433	0.1864	0.4207	0.1635
1900	0.18	0.189	0.1937	0.1163	0.169	0.2993	0.1284
2000	0.1729	0.1768	0.1847	0.1072	0.1619	0.2586	0.1174
2100	0.1674	0.1715	0.179	0.1033	0.1562	0.2451	0.1134
2200	0.1634	0.1673	0.1739	0.1005	0.151	0.2385	0.1103
2300	0.1602	0.164	0.17	0.098	0.1469	0.2329	0.1075
2400	0.1575	0.1615	0.1669	0.096	0.1438	0.2285	0.105
2500	0.1552	0.1593	0.1643	0.0941	0.1413	0.2242	0.1029
2600	0.1536	0.1572	0.1619	0.0925	0.1391	0.2201	0.1011
2700	0.1524	0.1551	0.1599	0.0912	0.1373	0.217	0.0995

Table 9 (continued)
Experiment result for the impact on SFC

Speed (rpm)	Resulted SFC						
	D100	**B10**	**B20**	**B30**	**D90 PH10**	**D80 PH20**	**D70 PH30**
2800	0.1515	0.1541	0.1584	0.0903	0.1362	0.2153	0.0985
2900	0.1507	0.1539	0.1576	**0.0898**	0.1352	0.2143	0.0979
3000	0.1508	**0.154**	0.1572	**0.0898**	0.1343	0.2133	0.0975
3100	**0.1515**	**0.154**	**0.1571**	0.0901	0.1336	**0.2125**	**0.0973**
3200	0.1516	**0.154**	0.1575	0.0903	**0.1335**	0.2126	0.0974
3300	0.1525	0.1542	0.1584	0.0907	0.1341	0.2139	0.0979
3400	0.1545	0.1557	0.1605	0.092	0.1353	0.2162	0.099
3500	0.1569	0.1594	0.1644	0.0936	0.137	0.2196	0.1004
3600	0.1609	0.1646	0.1686	0.0951	0.1394	0.2249	0.1019
3700	0.1658	0.1694	0.1727	0.097	0.1426	0.2321	0.1042
3800	0.1714	0.1727	0.1771	0.0994	0.1464	0.2389	0.1069
3900	0.1779	0.1784	0.1825	0.1026	0.1508	0.2459	0.1103
4000	0.1858	0.1878	0.1911	0.1071	0.1577	0.2566	0.1158
4100	0.1981	0.2042	0.2028	0.1123	0.167	0.2727	0.1225
4200	0.2005	0.3236	0.2886	0.2039	0.2393	1.0617	0.2696

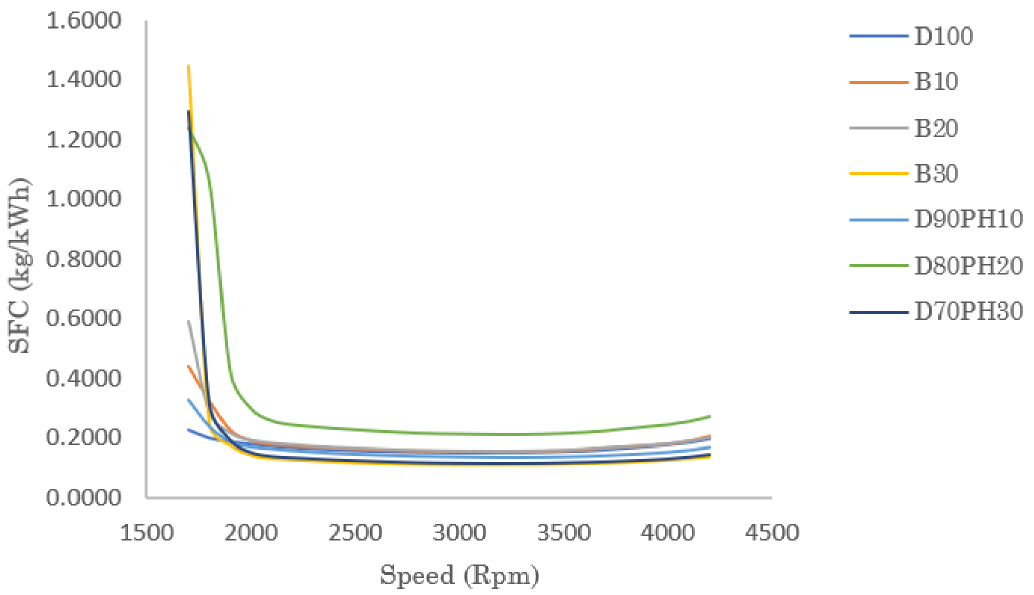

Figure 3
Relation between rotation speed and mixture to SFC

(Kanth & Debbarma 2021) stated that the additional hydrogenation in diesel fuel increased the performance and efficiency of the machine, particularly for SFC. Although the optimum mixture was produced when only mixing diesel with hydrogen, biodiesel was found to optimize SFC compared to standalone diesel.

A similar result was obtained by (Kaya & Kökkülünk 2023), which showed waste cooking oil as biodiesel optimized SFC. The results showed that 20% of biodiesel in mixture performed the best compared to 50% and 100%. In this research, 30% of biodiesel returned the most optimum SFC.

Mathematical Model

An attempt was made to establish two mathematical models to predict torque and power with a polynomial equation. In the model, the dependence variable (y) served as torque or power. The independent variables for every model were the mixture ratio and rotation in rpm (X). However, a model for SFC was not established due to direct relationship with power, which was considered redundant.

Mathematical Model for Torque

To predict torque in biodiesel mixture (B10, B20, B30), the model is written in Equation 3.

$$\begin{aligned} f_{torque-b}(x_i) = (-772.2){x_i}^4 &+ 26557.06{x_i}^3 \\ &- 342212.5{x_i}^2 \\ &+ 1959585.28x_i \\ &- 4206968.35 \end{aligned} \tag{3}$$

$$x_i = \frac{1}{(1+e^{-a_i})} + \ln(b_i)$$

In Equation 3, ai corresponds to biodiesel ratio in the mixture (for example, B30 has a value of 0.3 for a) and bi corresponds to rotation (rpm). The error between actual torsion and predicted torsion is visualized with scatter plot in Figure 4, where the x-axis shows actual torsion, and the y-axis indicates predicted torsion.

The average error for the model was 17.9%, which was significantly large but most errors occurred in low rotation. Based on the observation, most of the major errors occurred when rotation was relatively low below 2000 rpm or above 4000 rpm. For comparison, only one data point with rotation above 4000 rpm had more than 50% error. At rotation below 2000 rpm, the average error was found to be at 6.8%. Additionally, when data points with rotation above 4000 rpm were taken out as well, the average error significantly decreased to 5.3%.

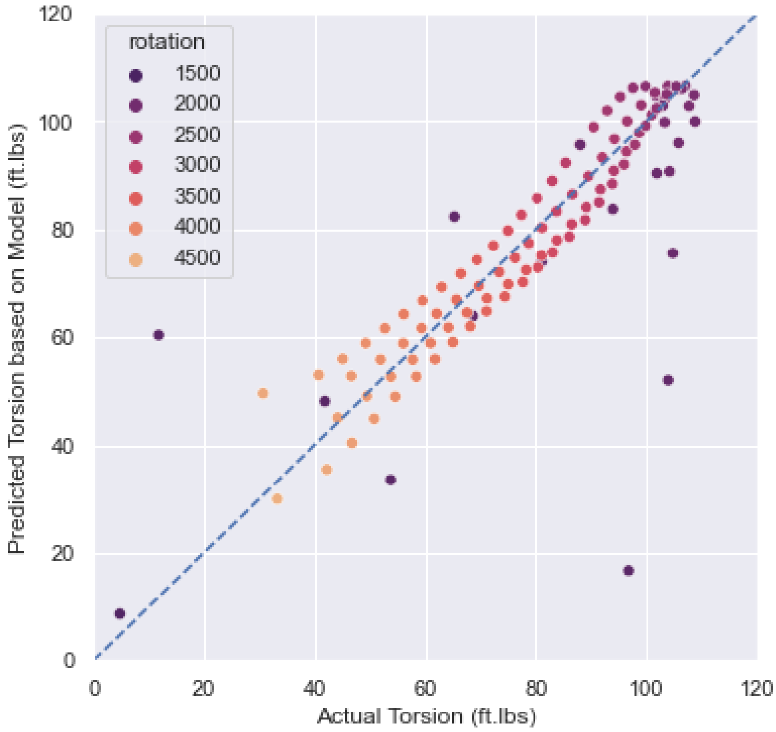

Figure 4
Scatter plot between actual torsion and predicted torsion in biodiesel mixture

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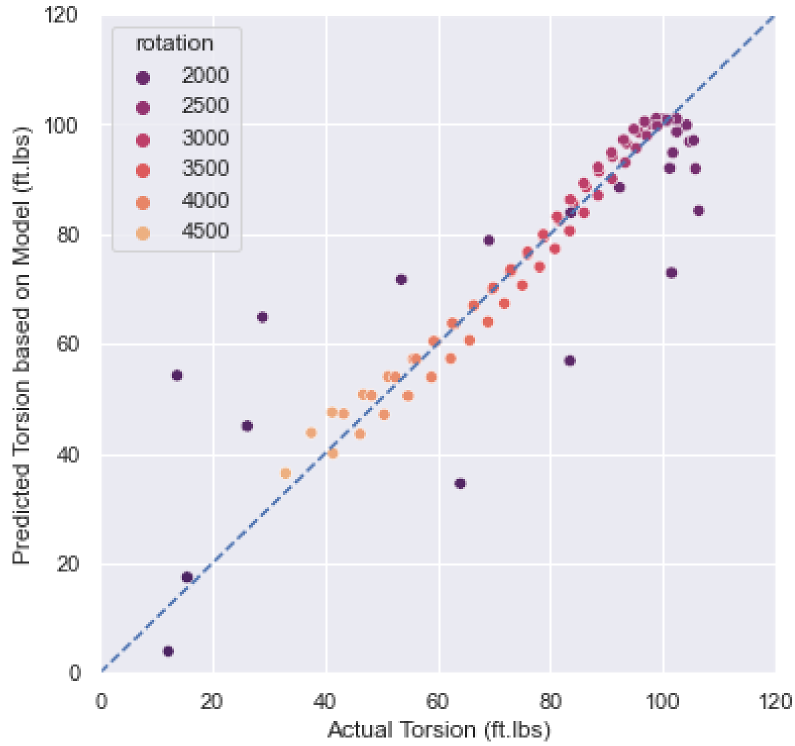

Figure 5
Scatter plot between actual torsion and predicted torsion in partially hydrogenated biodiesel mixture

This showed that the mathematical model in Equation 4 obtained an 11.9% average error between actual torsion and predicted torsion. Analogous to the prior model of biodiesel mixture, Figure 5 showed that the model error in prediction when rotation was below 2000 rpm. The average error decreased to 4.1% when rotation below 2000 rpm was neglected, which further reduced to 3.4% between 2000 rpm and 4000 rpm. Therefore, mathematical model is optimally applicable between 2000 rpm to 4000 rpm for biodiesel mixture.

For partially hydrogenated biodiesel (D90PH10, D80PH20, D70PH30), a similar method was performed to obtain a mathematical model based on ratio in the mixture and rotation. The model for predicting torque in partially hydrogenated biodiesel was written as in Equation 4. ai corresponds to biodiesel ratio in the mixture (for example, D80PH20 has a value of 0.2 for a), and bi shows rotation (rpm). The error between actual torsion and predicted torsion is shown with scatter plot in Figure 5, where the x-axis shows actual torsion, and the y-axis indicates predicted torsion.

$$\begin{aligned} f_{torque-ph}(x_i) = (-255.71)x_i^{4} \\ + 8931.53x_i^{3} \\ - 117045.76x_i^{2} \\ + 681957.6x_i \\ - 1490219.28 \end{aligned} \tag{4}$$

$$x_i = \frac{1}{(1+e^{-a_i})} + \ln(b_i)$$

Mathematical Model for Power

To predict power using mathematical model, biodiesel (B10, B20, B30) and partially hydrogenated biodiesel (D90PH10, D80PH20, D70PH30) mixtures are modeled into two different equations. Equation 5 performs power modeling based on biodiesel ratio in the mixture and rotation of the engine.

$$\begin{aligned} f_{power-b}(x_i) = (-112.61)x^4 \\ + 3859.22x_i^{3} \\ - 49656.74x_i^{2} \\ + 284328.2x_i \\ - 611206.46 \end{aligned} \tag{5}$$

$$x_i = \frac{1}{(1+e^{-a_i})} + \ln(b_i)$$

The actual power and predicted power based on Equation 5 for biodiesel mixtures is shown in Figure 6. Based on the results, most of the major errors appeared when rotation was at approximately 1500 rpm. There was a major error in rotation around 4500 rpm. This suggested that the model in Equation 5 optimally predicted power when rotation was between 2000 and 4000 rpm. The results were confirmed by the decline of average error between actual and predicted power. The average error for all rotations was 18.6%, while 2000 and 4000 rpm was 3.7%.

$$f_{power-ph}(x_i) = (-40.254)x^4 + 1370.66{x_i}^3 - 17600.86{x_i}^2 + 101021.74x_i - 218603.872 \quad (6)$$

$$x_i = \frac{1}{(1+e^{-a_i})} + \ln(b_i)$$

Equivalently, model was obtained for predicting power in partially hydrogenated mixture as written in Equation 6. ai symbolizes the ratio of partially hydrogenated biodiesel in the mixture, and bi corresponds to rotation. Based on the model, Figure 7 shows the actual and predicted power for partially hydrogenated biodiesel mixtures.

The model returns average error of 11.7% when all rotations are considered. Similar to the previous comparison, the errors decreased to 3.5% when considering only rotations between 2000 rpm and 4000 rpm. This result confirmed the previous statement that the modeling torsion and power produced accurate predictions, despite the mixture and its corresponding ratio.

Based on the calculated errors shown in Figures 4-7, the results showed that Equation 3-6 could be used to predict torque and power in biodiesel and partially hydrogenated biodiesel mixture. The equations use rotation per minute and ratio of fuel in the mixture. The models are optimized for rotation around 2000 until 4000 rpm.

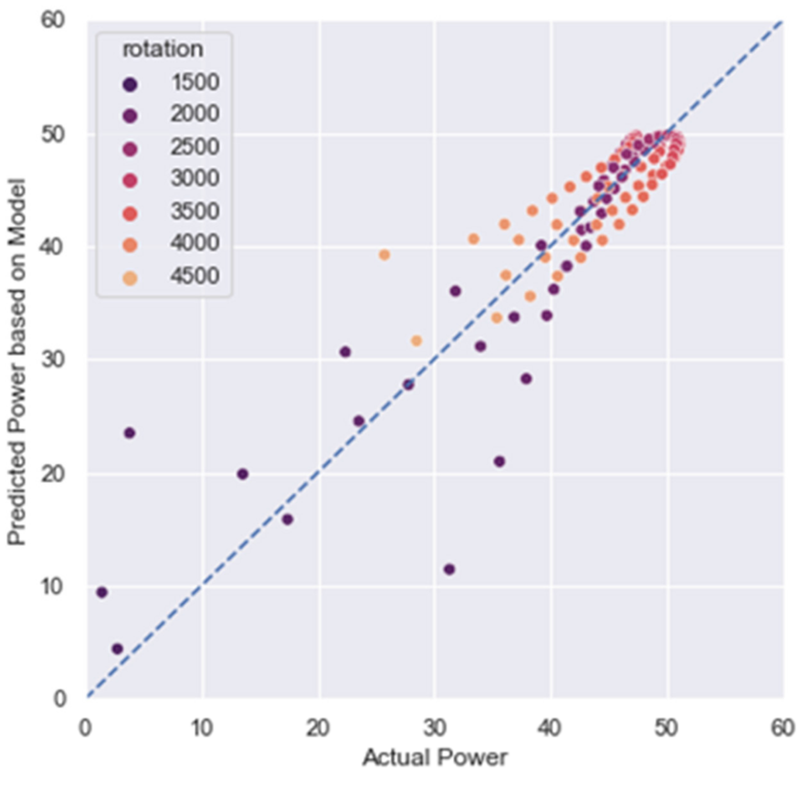

Figure 6
Scatter plot between actual power and predicted power in biodiesel mixture

CONCLUSION

In conclusion, this research successfully investigated the impact of biodiesel and partially hydrogenated biodiesel on diesel fuel mixture on torque, power, and SFC. The results showed better power, torque, and SFC compared to diesel fuel in multiple ratio and rotation. Furthermore, biodiesel and partially hydrogenated biodiesel were optimally used at around 2000 rpm. Based on the experiments, mathematical models were attempted to predict torque and power. The formulated models were optimized to be used at 2000 rpm and 4000 rpm, where ratio of biodiesel in mixture ranged from 10% to 30%.

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GLOSSARY OF TERMS

Symbol	Definition	Unit
SFC	Specific Fuel Consumption	kg/hp.hr
HP	Horse Power	hp
PS	Pferdestärke (horse power)	hp
rpm	Rotation per minute	rpm
e	Euler’s Number	-
TDC	Top dead centre	-
BDC	Bottom dead centre	-

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