Parameter Optimization for Enhanced Biodiesel Yield from *Linum usitatissimum* Oil Through Solar Energy Assistance

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Research Article

Keywords: Biodiesel, Linseed Oil, Taguchi's Method, Solar Paraboloid Dish, Response Surface Methodology

Posted Date: August 22nd, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1977661/v1

Abstract

Biodiesel is a biofuel produced from vegetable oils and animal fats. The study describes the solar-assisted biodiesel production from linseed oil and the parameter optimization using Taguchi's L_{27} orthogonal approach and response surface methodology (RSM). A solar paraboloid dish of collector area 6.1 m^2 and concentration ratio approx. 200 is used for the transesterification process. The yearly and daily solar radiation data shows that May-June has longer solar radiation availability during the daytime; and are favorable months for experimentation. The results show that Taguchi's approach gives a maximum biodiesel yield of 89.14%, while the RSM model offers a slightly higher 91.9% yield. However, the RSM analysis predicted 91.1% (maximum biodiesel yield) at molar ratio (MR) 8.92:1, reaction time (RT) 108.97 minutes, and catalyst concentration (CC) 0.61 wt.%, respectively. The ANOVA analysis found that the MR has the highest percentage contribution of 75.67%, followed by CC (15.9%) and RT (5.69%). The biodiesel composition is determined using gas chromatography, and the various other fuel properties are measured as per ASTM testing methods. The study successfully confirms the solar heating usage for the transesterification process.

1. Introduction

Energy is essential for developing infrastructure, industries, transportation, and meeting other basic needs. The energy is mainly extracted from fossil fuels like crude oil and coal. The extensive crude oil usage has become a significant economic problem for countries with lower crude oil reserves [1–3]. This situation has led to higher crude oil prices; thus, making a disbalance in the world's economy, but it has no impact on demand which is breaking records year by year. The crude oil burning also adds toxic gases to the air leading to increased annual death rates due to air pollution. These reasons are behind restricting and minimizing crude oil usage [4–6]. Therefore, the other compatible crude oil alternatives are being explored for many years; and biodiesel is one such alternative [6–8].

Biodiesel is an alkyl ester produced by the reaction between vegetable oil and alcohol in the presence of a catalyst [9]. Biodiesel has a very vast history; however, the higher production cost, raw material availability, and lower cost of available conventional crude oil never let it become a potential source to replace diesel [6]. Many researchers have tried different biodiesel extraction techniques to cope with these difficulties and worked with various edible and non-edible oils [10–13]. They also explored other sources for biodiesel production, including waste cooking oil, animal fats, and microalgae [14–16]. The higher free fatty acid (FFA) content in oils reduces the biodiesel yield, and thus, it needs to be lowered before the biodiesel production process. Therefore, a two-stage transesterification is performed to reduce the FFA content in the oil [8, 17].

Various techniques are available for biodiesel production. Mechanical stirring is the most familiar technique for biodiesel production. It is a less efficient technique because it gives comparably lower biodiesel yield than other techniques and consumes much energy, while the reaction time is in hours [2, 15, 18]. Another technique is an ultrasonic-assisted method. It uses ultrasonic waves to generate a cavitation effect within the mixture, which initiates the transesterification reaction faster and reduces the reaction time to 15–20 minutes with an improved biodiesel yield to about 92–95%. However, it demands tremendous energy to generate ultrasonic waves [15, 19]. The microwave-assisted method is another technique used to produce biodiesel. It is an advanced technology that gives a biodiesel yield of up to 96–99% within 5–7 minutes [20–22]. However, the higher energy demand and smaller batch production make it impracticable for commercial-scale production. Researchers and scientists are working on different techniques capable of continuous biodiesel production from various feedstocks at a lower cost [23–25].

Maintaining the temperature for transesterification reaction consumes the maximum energy in the biodiesel production process. Thus, renewable energy sources such as solar heat or waste heat from power plants must be considered [27–29]. Solar energy is dynamic in nature and available only during the daytime. Figure 1 shows the average monthly solar radiation availability and clearness index of Northern India throughout the year. The daily radiation from March to June is excellent for utilizing maximum solar energy, and different regions can be considered accordingly. Solar heat energy can efficiently replace conventional heating sources for biodiesel production [30, 31]; however, the solar devices should be chosen according to the temperature required for the reaction [32, 33]. The waste heat from the power plant is also a good heating source, but transferring it to a distant location is a difficult task [34].

In this experimental study, the solar-assisted method produces biodiesel from *Linum usitatissimum* (linseed oil), and the parameters are optimized using Taguchi's L_{27} orthogonal approach that are further optimized for enhanced biodiesel yield using response surface methodology (RSM). A solar parabolic dish of an area of 6.1 m^2 and approx. 200 concentration ratio is used to provide heating for the transesterification process. The study aims to find solar heat energy's potential to replace conventional heating sources in biodiesel production process. The current experimentation is for small batch-type biodiesel production; however, the study explored the possibility of using solar heat energy in a commercial-scale biodiesel production process. Therefore, the future work may focus on designing a continuous biodiesel production equipment compatible with solar energy.

2. Materials And Method

2.1 Solar Survey

Data for solar radiation with cloud clearness is collected every month throughout the year from earlier published works [26, 35]. It helps determine the suitable months for experimental work in Delhi Technological University, Delhi, India (28.7497° North and 77.1188° East). The study shows that the second half of May (15th -31st May) to the first half of June (1st-15th June) is the best possible period to perform experimentations because the maximum sunshine days are available during this period.

Solar radiation behavior is understood by a Tenmars TM-207 solar power meter (Fig. 2), which measures solar irradiation falling on earth. The reading is collected at every 30 minutes throughout the day before and between the experimentation. The solar radiation graph shows a similar trend for each day, rising from morning to afternoon and then declining (as shown in Fig. 3). Thus, the day is divided into three sessions, namely, morning (10:30 am to 12:30 pm), afternoon (12:30 pm to 2:30 pm), and post-afternoon (2:30 pm to 4:30 pm); and every experiment is performed in all three sessions of the day randomly, and the average reading is considered for calculations.

2.2 Materials

The matured seeds of *Linum usitatissimum* (linseed) are collected from the local market nearby the college campus of Delhi Technological University, Delhi, India, and the oil extraction is done by mechanical pressing [36]. Thus, the linseed oil is chosen as the raw material for biodiesel (methyl ester) production. Alcohol used in the process is industrial-grade methyl alcohol, while the catalyst taken is potassium hydroxide (KOH) with 56.11 molecular weight. The ranges of process parameters are chosen from the earlier published works [37–39], i.e., alcohol/oil ratio or molar ratio (MR) 6:1, 7.5:1 and 9:1, and catalyst concentration (CC) 0.5, 0.75 and 1.0 wt.%. However, the reaction time (RT) chosen are 90, 105 and 120 minutes taking into account the dynamic nature and availability of solar radiation throughout the day.

2.3 Biodiesel production method

Raw linseed oil is initially heated in a vessel at about 110°C using a conventional heater for approximately 10 minutes for moisture removal because moisture may lead to the saponification process, which eventually reduces the biodiesel yield [13]. The warm raw linseed oil is then allowed to cool down below 65°C before adding the catalyst-alcohol solution. Meanwhile, a methanol and catalyst KOH solution is prepared by mechanically dissolving KOH in methanol. The catalyst-alcohol solution is then poured into the raw linseed oil, and the container is sealed to prevent methanol vapors escape during the transesterification process. An aluminium foil covers the sealed container to restrict the UV radiation entering the container, which may cause radical formation. The aluminium foil also provides uniform heating to the sample. Next, the container is placed at the container stand (the focus of the solar receiver) to allow solar radiation to strike the aluminium foil and provide heat for the transesterification process. The solar receiver used is a solar paraboloid dish shown in Fig. 4, having a 6.1 m^2 collector area with a maximum temperature generation of 115ºC at 900–1000 W/m^2 solar irradiance and a concentration ratio of approx. 200. During the experiments, about 600–850 W/m^2 solar irradiance generating a temperature range between 75°C and 95°C is attained inside the container.

Once a sample is processed, it is transferred to a conical separating funnel and then kept undisturbed for about 8–10 hours to settle heavy glycerol in the sample. After the glycerol settles, it is taken out from the sample. The remaining liquid still contains dissolved KOH and traces of glycerol, which is removed by the water washing process. The water washing is performed by adding warm water to the biodiesel and allowing it to settle for another 3–4 hours. The KOH dissolved water is then taken out, and the rest of the biodiesel is again heated to 105°C using a conventional heater for removing any moisture left out during water washing [40]. The final product obtained is pure linseed methyl ester (LSME) or linseed biodiesel.

2.4 Design of Experiment

The robust designs for statistical calculations are developed using Taguchi's methods for engineering problems. These methods are simple and efficiently optimize the process parameters. An orthogonal L_{27} array is framed to assess the effects of various biodiesel production parameters at their different levels. The chosen parameters and their levels are represented in Table 1. It presents the complete evidence of parameters influencing the biodiesel yield [41, 42].

Table 1
Parameters and their levels for orthogonal L_{27} Taguchi's approach

Design Factors		Units	Level		
			1	2	3
A	Molar Ratio (MR)	—	6:1	7.5:1	9:1
B	Reaction Time (RT)	min.	90	105	120
C	Catalyst Concentration (CC)	wt.%	0.50	0.75	1.00

The signal to noise (S/N) ratio measures the experimental deviation to the desired value of performance parameters. The three types of S/N ratio are Larger the Better; Smaller the Better; and Nominal the Better [42, 43]. For biodiesel production, the Larger the Better S/N ratio is used. Here, the result is computed to get the maximum value of the response (biodiesel yield). The equation used in the process is as given by Eq. 1: -

$$S/Nratio = -10log_{10}\left\{\frac{1}{n}\sum_{j=1}^{N}\left(\frac{1}{Y_j^2}\right)\right\}$$

1

where n = number of responses in the factor level combination; and

Y_j = responses for the given factor level combination

3. Results And Discussion

Biodiesel Production

Current work focuses on maximizing biodiesel yield using Taguchi's approach and response surface methodology (RSM). In Table 2, the rank of all the parameters is computed along with the S/N ratios at different levels. Here, the delta value is used for determining the ranks of performance parameters, the highest delta value denotes rank 1, and so on. Hence, the molar ratio with rank 1 is identified as the most effective performance parameter in biodiesel production.

Table 2. Response table of operating parameters

Parameters	Level			Delta	Rank
	1	2	3		
Molar Ratio (oil/methanol)	38.17	38.43	38.79	0.60	1
Reaction Time (minutes)	38.38	38.55	38.48	0.23	3
Catalyst Concentration (wt.%)	38.59	38.48	38.31	0.13	2

Table 3 depicts the biodiesel yield (in percentage) obtained for each run (or experiment) in each day session. Data shows less than 1% deviation in biodiesel yield; thus, the mean value of three sessions is considered for further calculations. The mean biodiesel yield (in percentage) at various experiments (or run) and the S/N ratios are also given in Table 3. The mean biodiesel yield ranges from 77.45% (minimum) to 89.14% (maximum), and similar results are obtained by *Kumar et al.* (2017) [42] and *Kumar et al.* (2018) [43]. The highest mean yield of 89.14% is obtained in run 26 by MR 9:1, RT 120 mins. and CC 0.75 wt.%. Also, the optimum condition, which is measured by the highest value of the S/N ratio (38.94), is achieved by two experiments, i.e., run 22 and run 26, respectively.

Table 3. Biodiesel yield and S/N ratio of L_{27} experiments performed

Run	Molar Ratio	Reaction Time (min.)	Catalyst Conc. (wt. %)	Biodiesel Yield (%)			Mean Yield (%)	S/N ratio
				Morning	Afternoon	Post-Afternoon		
1	6:1	90	0.5	80.23	80.32	80.29	80.28	38.18
2	6:1	90	0.75	81.22	81.29	81.21	81.24	38.15
3	6:1	90	1	77.43	77.44	77.48	77.45	37.74
4	6:1	105	0.5	84.59	84.67	84.57	84.61	38.56
5	6:1	105	0.75	82.11	82.23	82.17	82.17	38.24
6	6:1	105	1	78.73	78.97	78.91	78.87	37.97
7	6:1	120	0.5	84.76	85.18	85.06	85.00	38.49
8	6:1	120	0.75	81.67	81.71	81.72	81.70	38.34
9	6:1	120	1	77.81	78.00	77.95	77.92	37.84
10	7.5:1	90	0.5	83.97	84.11	84.13	84.07	38.42
11	7.5:1	90	0.75	81.59	81.76	81.78	81.71	38.30
12	7.5:1	90	1	83.08	83.11	83.17	83.12	38.42
13	7.5:1	105	0.5	86.34	86.43	86.49	86.42	38.75
14	7.5:1	105	0.75	82.57	82.67	82.71	82.65	38.33
15	7.5:1	105	1	84.89	84.91	84.96	84.92	38.58
16	7.5:1	120	0.5	83.58	83.57	83.62	83.59	38.50
17	7.5:1	120	0.75	82.12	82.16	82.23	82.17	38.26
18	7.5:1	120	1	82.19	82.27	82.32	82.26	38.28
19	9:1	90	0.5	85.99	86.12	86.19	86.10	38.69
20	9:1	90	0.75	88.31	88.34	88.34	88.33	38.92
21	9:1	90	1	85.29	85.33	85.40	85.34	38.64
22	9:1	105	0.5	88.73	88.79	88.79	88.77	38.94
23	9:1	105	0.75	87.14	87.12	87.16	87.14	38.87
24	9:1	105	1	86.83	86.78	86.76	86.79	38.73
25	9:1	120	0.5	86.94	87.00	86.94	86.96	38.83
26	9:1	120	0.75	89.11	89.16	89.15	89.14	38.94
27	9:1	120	1	84.51	84.55	84.50	84.52	38.56

Initially, the effects of operating parameters on the response are analyzed using Taguchi's approach, and Fig. 5 shows the impact of different operating parameters on the biodiesel yield at all three levels. The peak value defines the optimum value of all parameters for different S/N ratio plots. Consequently, MR 9:1 (level 3), RT 105 min. (level 2), and CC 0.5 wt.% (level 1) achieves the highest biodiesel yield. It indicates that the above process parameters are required to obtain the maximum biodiesel yield at the optimized conditions.

Regression analysis is performed by the data acquired in biodiesel yield from eq. 2, and the percentage of the coefficient of regression (97.72%) is given by eq. 3: -

$$Yield = 5.9 + 1.72\ MR + 1.379\ RT + 1.79\ CC + 0.584\ (MR)^2 - 0.00588\ (RT)^2 - 0.306\ (CC)^2 - 0.0267\ MR*RT + 0.873\ MR*CC - 0.0351\ RT*CC \quad (2)$$

$$R^2 = 97.72\% \quad (3)$$

Experimental and predicted values of biodiesel yield and the error percentage in different experiments of Taguchi's L_{27} approach are given in Table 4. The result shows a very close relationship between the experimental and predicted values of biodiesel yield. The experimental yield values (%age) show a minimal deviation from predicted yield values (%age), and the difference is measured as the mean error percentage for each experimentation. The highest mean error percentage is about 1.17%, which indicates that the experimental yield values are not more than 1.2% deviated from the predicted yield values.

Table 4. Experimental and predicted values for Taguchi's L_{27} approach

Experiment (Run)	Molar Ratio	Reaction Time (min.)	Catalyst Conc. (wt. %)	Yield (%)		Error (%)
				Experimental	Predicted	
1	6:1	90	0.5	80.28	81.07	0.9884
2	6:1	90	0.75	81.24	80.81	-0.5186
3	6:1	90	1	77.45	77.07	-0.4807
4	6:1	105	0.5	84.61	84.79	0.2045
5	6:1	105	0.75	82.17	81.64	-0.6481
6	6:1	105	1	78.87	79.23	0.4558
7	6:1	120	0.5	85.00	84.04	-1.1371
8	6:1	120	0.75	81.70	82.65	1.1675
9	6:1	120	1	77.92	77.93	0.0163
10	7.5:1	90	0.5	84.07	83.37	-0.8268
11	7.5:1	90	0.75	81.71	82.19	0.5908
12	7.5:1	90	1	83.12	83.33	0.2556
13	7.5:1	105	0.5	86.42	86.55	0.1503
14	7.5:1	105	0.75	82.65	82.48	-0.1973
15	7.5:1	105	1	84.92	84.95	0.0390
16	7.5:1	120	0.5	83.59	84.16	0.6761
17	7.5:1	120	0.75	82.17	81.85	-0.3890
18	7.5:1	120	1	82.26	82.01	-0.2984
19	9:1	90	0.5	86.10	86.00	-0.1143
20	9:1	90	0.75	88.33	88.27	-0.0696
21	9:1	90	1	85.34	85.50	0.1873
22	9:1	105	0.5	88.77	88.47	-0.3413
23	9:1	105	0.75	87.14	87.84	0.7983
24	9:1	105	1	86.79	86.40	-0.4524
25	9:1	120	0.5	86.96	87.36	0.4616
26	9:1	120	0.75	89.14	88.50	-0.7114
27	9:1	120	1	84.52	84.75	0.2754

Analysis of variance (ANOVA)

ANOVA determines the significance of various parameters in the process. The ANOVA analysis (as represented in Table 5) defines the importance of process parameters for biodiesel yield. The significance of a model is determined by its p-value (<0.0500), where a higher p-value states the process parameter is insignificant. In this case, MR and CC have a p-value of 0.000, making them highly significant model terms, while RT has a p-value of 0.011; thus, it is also a significant model term but less effective than MR and CC.

Table 5. ANOVA table for biodiesel yield

Source	**Degree of Freedom**	**Seq. SS**	**Adj. SS**	**Adj. MS**	**F-value**	**P-value**	**Contribution (%)**
MR	2	163.115	163.115	81.5573	110.46	0.000	75.67
RT	2	12.262	12.262	6.1308	8.30	0.011	5.69
CC	2	34.278	34.278	17.1391	23.21	0.000	15.90
MR*RT	4	4.834	4.834	1.2084	1.64	0.256	---
MR*CC	4	29.056	29.056	7.2641	9.84	0.004	---
RT*CC	4	9.320	9.320	2.3300	3.16	0.078	---
Residual Error	8	5.907	5.907	0.7383			2.74
Total	26	258.771					100

Percentage contribution of MR, RT, and CC is also computed using the ANOVA table (Table 5), where Seq. SS terms are considered for calculating the percentage contribution of a parameter in the process. The highest contributing parameter is the molar ratio (75.67%), followed by catalyst concentration (15.9%) and reaction time (5.69%), while a residual error of 2.74% is also observed. It indicates that a slight variation in the molar ratio will significantly affect biodiesel yield.

Response surface methodology (RSM)

RSM is based upon the different mathematical and statistical practices established through the experimental design of adequate empirical models. It shows the relationship between the observed and theoretically obtained values from different empirical models. Fig. 6 depicts a connection between predicted values and actual values for biodiesel yield in percentage; it also shows the closeness of the two values.

Response surface methodology (RSM) also gives the interactive effects between different factors in surface-contour plots, which helps better understand the effects of two factors on response [44]. The surface-contour plots for the above experiments are shown in Fig. 7, 8, and 9. In Fig. 7, the effects of MR and CC are depicted, while the RT is taken as 105 min. (actual factor). The value of RT is taken from Taguchi’s approach, which gives optimized biodiesel yield at 105 min. The figure shows that biodiesel production enhances when MR (alcohol to oil) is higher that is similar to the results obtained by *Fan et al. (2011)* [44]. Consequently, the catalyst concentration between 0.6 and 0.9 wt.% shows a slight decline, going against the findings of *Yadav et al.* (2018) [45]. However, the plot shows the potential for higher biodiesel yield with the rise in molar ratio beyond 9:1.

The interactive effects between CC and RT are represented in Fig. 8. Here, the curve's flatness shows a lower percentage contribution of these parameters, as described in the ANOVA table (table 5). CC and RT's percentage contributions are less than MR; thus, putting molar ratio to 9:1 (actual factor) will show less fluctuation in the surface counter curve. The transesterification process in solar-assisted biodiesel production takes more time than conventional methods; as a result, the optimized RT is observed between 95 and 110 mins. However, after 110 mins, a decline in biodiesel yield is observed due to reverse reaction. Similar observations are also noticed by *Mihankhah et al.* (2016) [12].

In Fig. 9, the interaction of RT with MR is shown for biodiesel yield (as a response). As discussed, the biodiesel yield rises with the molar ratio; thus, a similar trend is observed in the figure. Higher molar ratio with RT more than 95 min. gives more than 83% of biodiesel yield. From different published works, it was observed that the transesterification process requires a 3:1 M ratio (alcohol to triglyceride) for alkyl ester (biodiesel) conversion [46, 47]; however, to get a biodiesel yield greater than 80%, an MR of 9:1 or more is favorable. In contrast, the higher MR results in extra alcohol content, creating difficulty in glycerol separation. Thus, a relevant MR between 9 and 12 is acceptable for biodiesel production, while a higher MR of 15:1 reduces the biodiesel yield due to difficulty in glycerol recovery [33, 45]. RSM analysis concluded that the optimized parameters for desirable biodiesel yield (91.1%) are molar ratio 8.92:1, reaction time 108.97 minutes, and catalyst concentration 0.61 wt.%, respectively. Five consecutive experiments are performed to confirm the values obtained through the RSM model, and the average of the five experiments is found to be 91.9% biodiesel yield.

Fuel properties

For considering any fuel for internal combustion (IC) engines, the fuel properties must match the engine input parameters as per ASTM standards. Thus, the desirable fuel properties are measured for biodiesel (LSME) and raw linseed oil, and compared with diesel. Table 6 compares desirable fuel properties of LSME and diesel as per ASTM testing methods.

Table 6. Desirable fuel properties for CI engine

Properties	ASTM Testing method	SI Unit	Diesel	Raw linseed oil	Linseed methyl ester (LSME)		
					This work	[48]	[49]
Density at 15°C	D-1298	kg/m^3	809.6	914.0	869.8	860	872
Kinematic viscosity at 40°C	D-445	$\times 10^{-6}$ m^2/s	2.815	27.317	5.453	5	8.2
Calorific value	D-240	$\times 10^{3}$ kJ/kg	45.5	35.2	36.7	35.6	37.5
Flash point	D-93	°C	72	>210	162	187	161
Pour point	D-97	°C	-9	-15	-11	---	---
Cetane index	D-4737	---	48.1	40.2	42.7	---	55

The density of the conventional diesel is 809.6 kg/m^3, whereas raw linseed oil has a higher density of 914.0 kg/m^3. After the transesterification of linseed oil, the linseed methyl ester (LSME) is produced [50], and the density is reduced to 869.8 kg/m^3, which is under the ASTM standards [1]. In contrast, the kinematic viscosity of LSME is found to be 5.453×10^{-6} m^2/s which is twice of diesel (2.815×10^{-6} m^2/s) and is close to the upper limit of the ASTM standards [1, 13].

The calorific value (CV) of a fuel is the heating capacity of the fuel or the energy released when the fuel is burnt. The CV of diesel is measured maximum (45.5×10^3 kJ/kg), and LSME is measured about 36.7×10^3 kJ/kg. Flash point and pour point of LSME are 162°C and -11°C, while the cetane index is 42.7, respectively. Hence, it is concluded that the desirable properties of biodiesel are comparable to diesel (under ASTM standards) [1, 13]. As a result, a biodiesel blend with diesel could be used in the existing CI engines with no modifications, or pure biodiesel could directly be used with few modifications in the CI engine.

Fatty acid methyl ester (FAME) composition

The FAME composition of the oil is an essential parameter. It gives the composition of all the FAME content present in the biodiesel. Ultima make series 2100 gas chromatography (specifications in Table 7) is used to measure the FAME composition of biodiesel (LSME).

Table 7. Specifications of gas chromatography

Make	Ultima
Model	Series 2100
Detector	Flame ionization detector (FID)
Carrier gas	Nitrogen
Other gases	Hydrogen and zero air
Oven temperature	240°C
Rate of temperature rise	10°C/min

The gas chromatogram for LSME is shown in Fig. 10. The curve shows the different FAME compositions in percentage, while Table 8 presents the FAME composition of linseed methyl ester (LSME).

Table 8. FAME composition in wt.%

Fatty acid	Chemical formula	Degree of Saturation	Linseed methyl ester		
			This work*	[51]*	[52]*
Palmitic	$C_{16}H_{32}O_2$	16:0	5.41	6.58	5.69
Stearic	$C_{18}H_{36}O_2$	18:0	4.94	4.43	5.58
Oleic	$C_{18}H_{34}O_2$	18:1	18.73	18.51	20.59
Linoleic	$C_{18}H_{32}O_2$	18:2	15.95	17.25	15.80
Linolenic	$C_{18}H_{30}O_2$	18:3	54.12	53.21	51.38
Total saturated	-	-	10.45	11.01	11.90
Total unsaturated	-	-	89.35	88.99	88.10

*All values are in wt.%

The linolenic acid content is highest (54.12%) in LSME, whereas other higher fatty acids are linoleic acid (15.95%) and oleic acid (18.73%). However, a small quantity of palmitic acid (5.41%) and stearic acid (4.94%) is also present in the linseed methyl ester (as depicted in Table 8). The experimentally obtained FAME values are comparable to earlier work, and it is found that the values obtained (Table 8) do not differ significantly from other published data [36, 51–53].

Comparative analysis of results

A detailed comparison of various biodiesel production methods with feed oil is represented in Table 9. It is concluded that solar-assisted biodiesel production is well competitive with other techniques in biodiesel yield. However, the zero-power requirement in the solar-assisted process makes it superior to other methods.

Table 9. Comparative analysis of present work and other published works

Reference	Feed oil	Methods used	Power	Biodiesel yield
Predicted	Linseed oil	---	---	91.1%
Experimental (RSM model)	Linseed oil	Solar-assisted	0	91.9%
Experimental (ANOVA)	Linseed oil	Solar-assisted	0	91.6%
Mohite et al. [13]	Karanja-Linseed oil mixture	Mechanical starring and conventional heating	180 W	78.9%
Singh et al. [15]	Microalgae oil	Ultrasonic	50 W	98%
Uddin et al. [16]	Waste cooking oil	Mechanical starring and conventional heating	210 W	79%
Hsiao et al. [20]	Soybean oil	Microwave-assisted	300 W	96.6%
Kumar et al. [21]	Pongamia pinnata seed oil	Microwave-assisted	300 W	96%
Mohan et al. [40]	Semal oil	Ultrasonic cavitation and mechanical stirring	780 W	90.7%
Kumar et al. [43]	Pongamia oil	Mechanical starring and conventional heating	180 W	90.2%

*Bold is used to represent present work results

4. Conclusions

Biodiesel is produced from the reaction between Linum usitatissimum oil (linseed oil) and methanol in the presence of KOH. A solar paraboloid dish of a 6.1 m^2 collector area and approx. 200 concentration ratio provides heat energy for the transesterification process. An L_{27} orthogonal array is designed using Taguchi's approach with the molar ratio, reaction time, and catalyst concentration at three different levels. RSM and ANOVA analysis are performed to optimize process parameters and determine their percentage contribution in biodiesel production. The confirmation experiment is performed to validate the optimized parameter values obtained using RSM. The following findings are obtained from the study: -

- During the daytime, the solar paraboloid dish attained a temperature of 75–95°C at about 600–850 W/m^2 solar radiation.
- Taguchi's L_{27} orthogonal array experimentally achieves the highest mean biodiesel yield of 89.14%.
- FAME content in LSME is characterized using GC, and the various biodiesel properties are determined as per ASTM testing methods.

- Optimized parameters using RSM analysis are MR 8.92:1, RT 108.97 minutes, and CC 0.61 wt.% producing 91.1% of predicted biodiesel yield.
- Experimental biodiesel yield of 91.9% is achieved using the RSM model at optimized parameters and comparable with other published works.
- ANOVA analysis showed the maximum contribution of MR (75.67%), followed by CC (15.9%) and RT (5.69%), respectively.
- Taguchi's approach provides interaction of all parameters; however, the RSM analysis is better due to the higher interaction of all process parameters.

Thus, the study showed the excellent potential of using solar heat energy for biodiesel production, reducing the dependence on conventional heating sources.

5. Future Scope

The current study is performed in a small-scale batch-type biodiesel production process to understand the potential of using solar heat energy in the transesterification process. The study shows comparatively good biodiesel yield without using any conventional heating source during the transesterification process. However, commercial-scale biodiesel production requires an efficient solar capturing device. Thus, future research can focus on finding the potential of other solar heat capturing devices and raising the biodiesel yield for continuous biodiesel production at a commercial scale.

Declarations

Acknowledgment

This work is supported by the Delhi Technological University, Delhi, India. The authors are thankful for all the support provided by the IC Engine lab, Mechanical Engineering Department, DTU for conducting experiments.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Conflicts of interest/Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Consent for publication

Authors have agreed to submit it in its current form for consideration for publication in the journal.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by *Neeraj Budhraja*. The first draft of the manuscript was written by *Neeraj Budhraja* and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Availability of data and material

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request. Additional data (figures showing experimental setup and gas chromatography) is presented in the Supplementary file.

Ethics approval and consent to participate

Not applicable. No tests, measurements or experiments were performed on humans as part of this work.

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Supplementary Material

Supplementary Information not available with this version.

Figures

Figure 1

Annual solar radiation and clearness index of Northern India [26]

Figure 2

Solar power meter

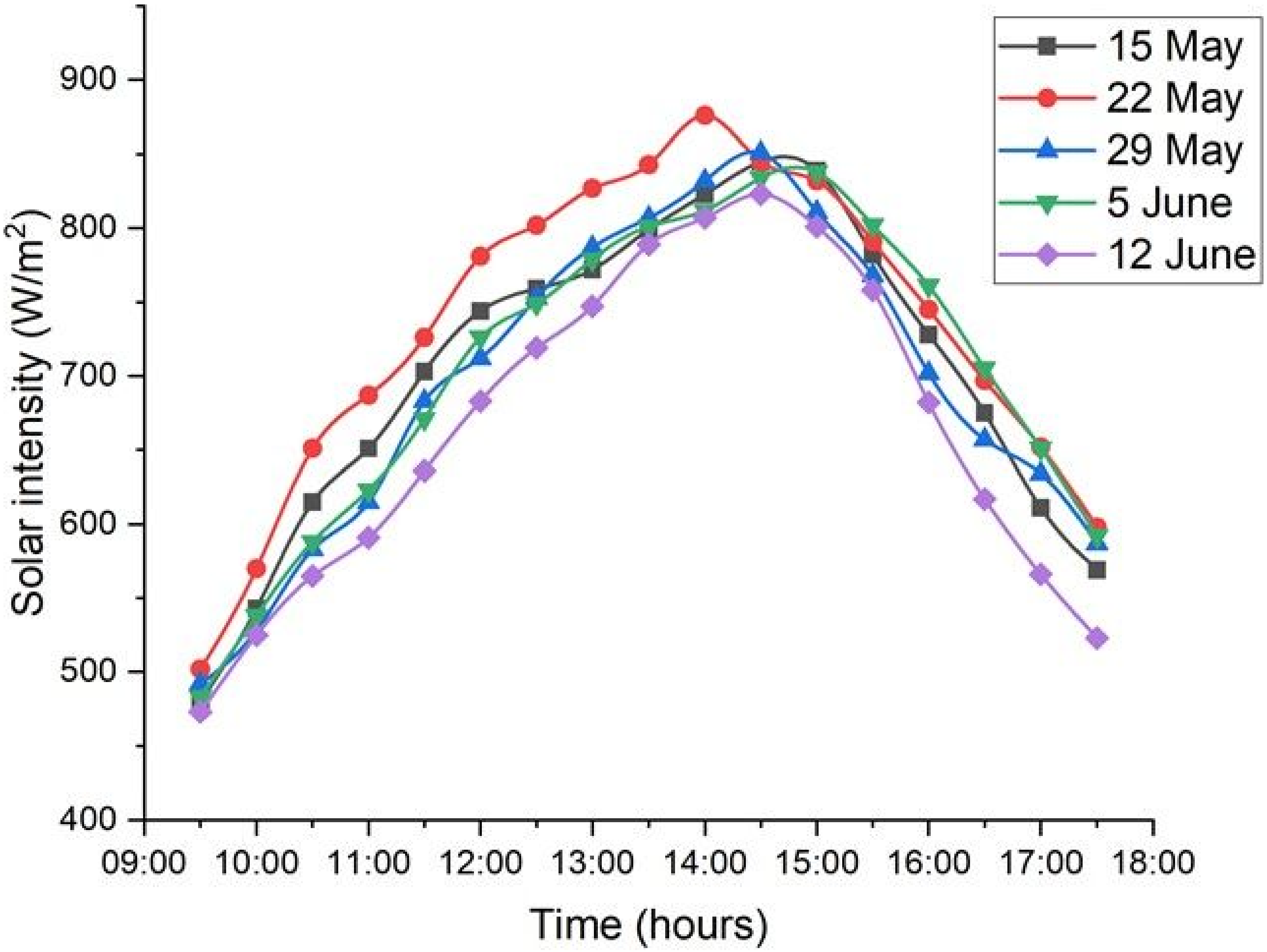

Figure 3

Daily solar radiation curve for Delhi

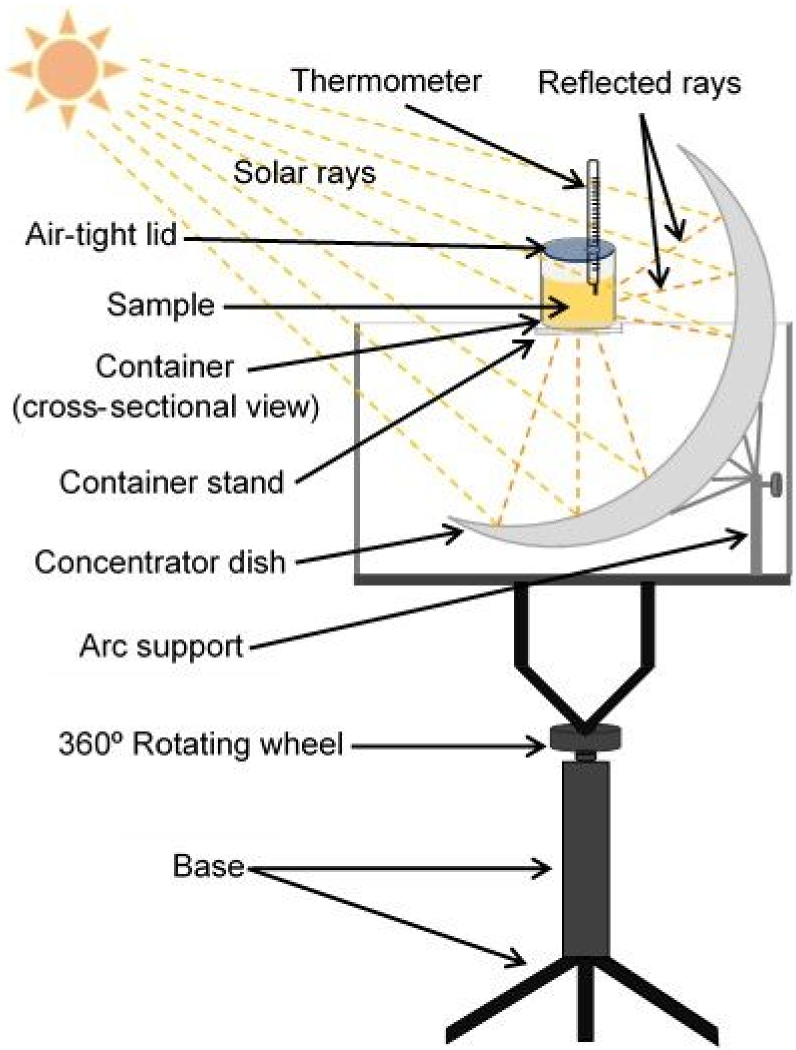

Figure 4

Solar paraboloid dish experimental setup

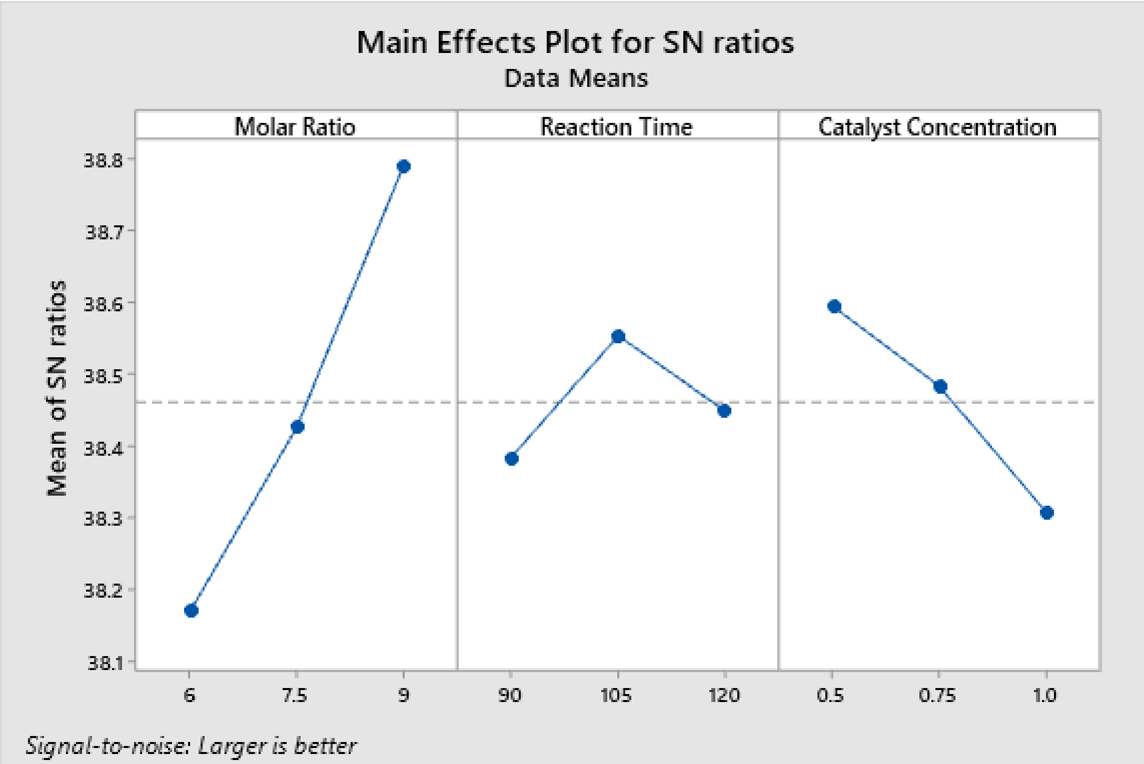

Figure 5

Effects of S/N ratios (Larger is Better) on various parameters

Figure 6

Predicted vs. actual value relationship for biodiesel yield percentage

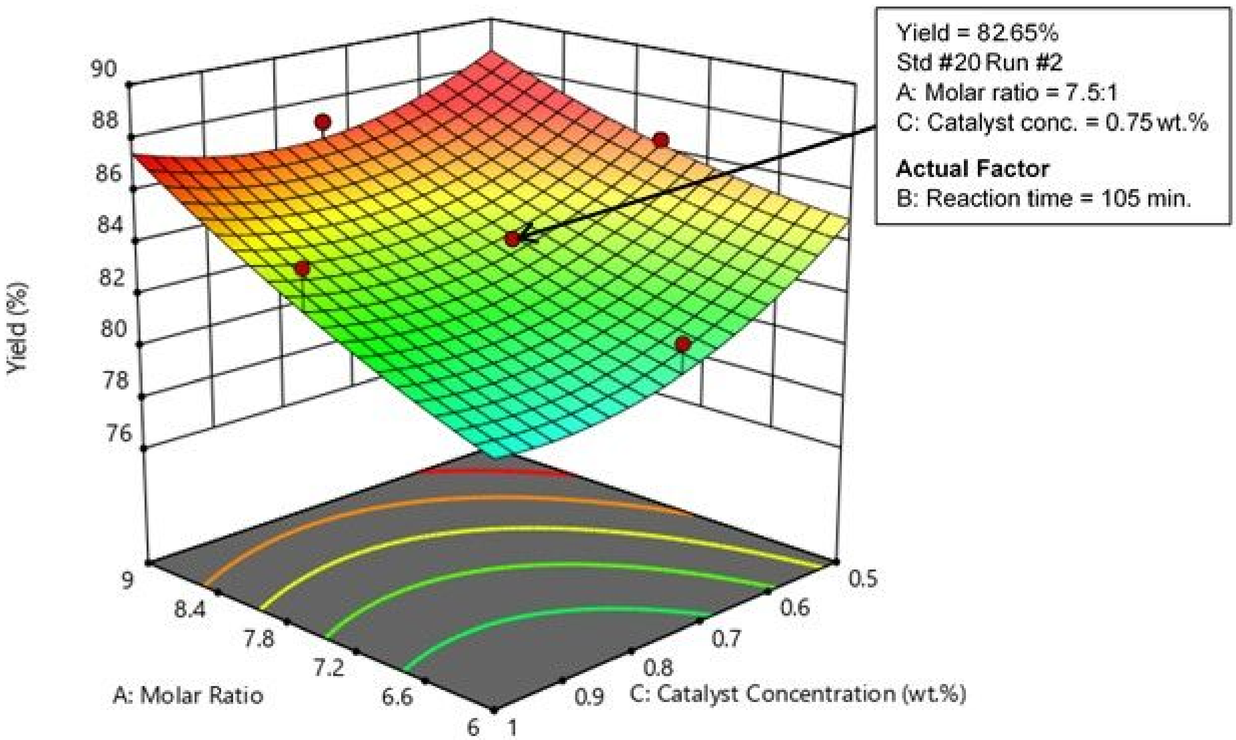

Figure 7

Interaction surface response curve between CC (wt.%) and MR

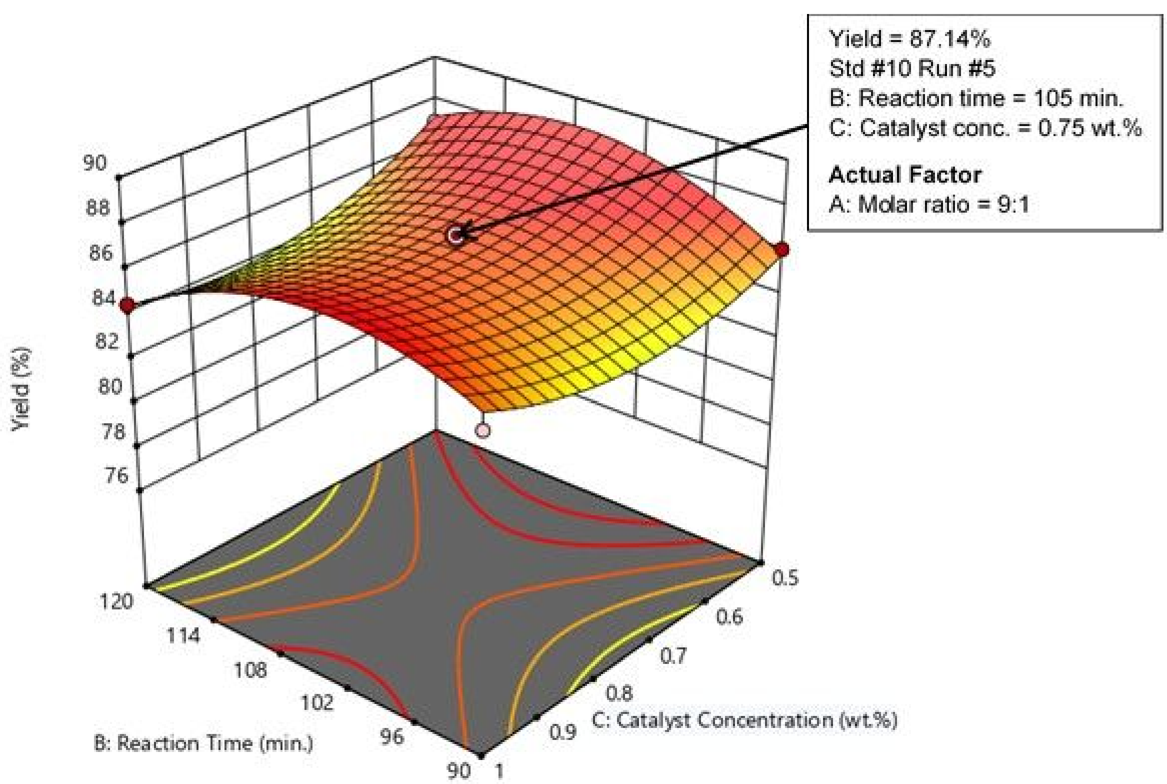

Figure 8

Interaction surface response curve between CC (wt.%) and RT (min.)

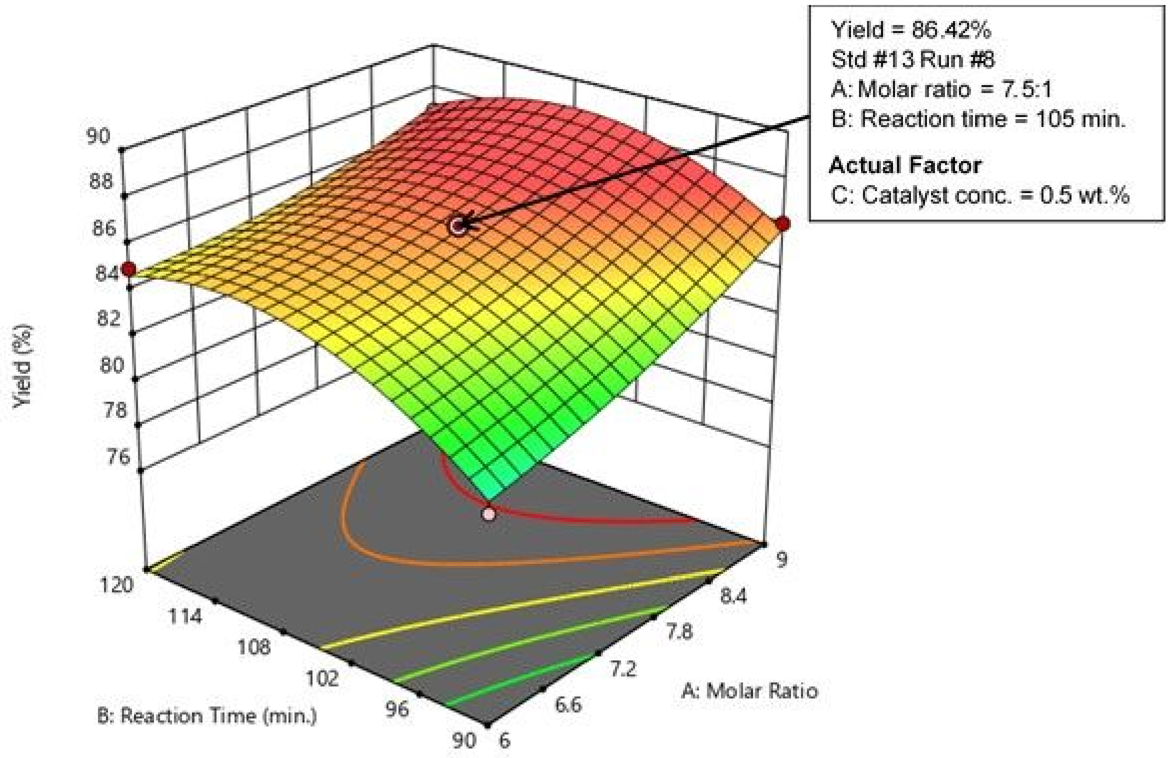

Figure 9

Interaction surface response curve between RT (min.) and MR (alcohol to oil)

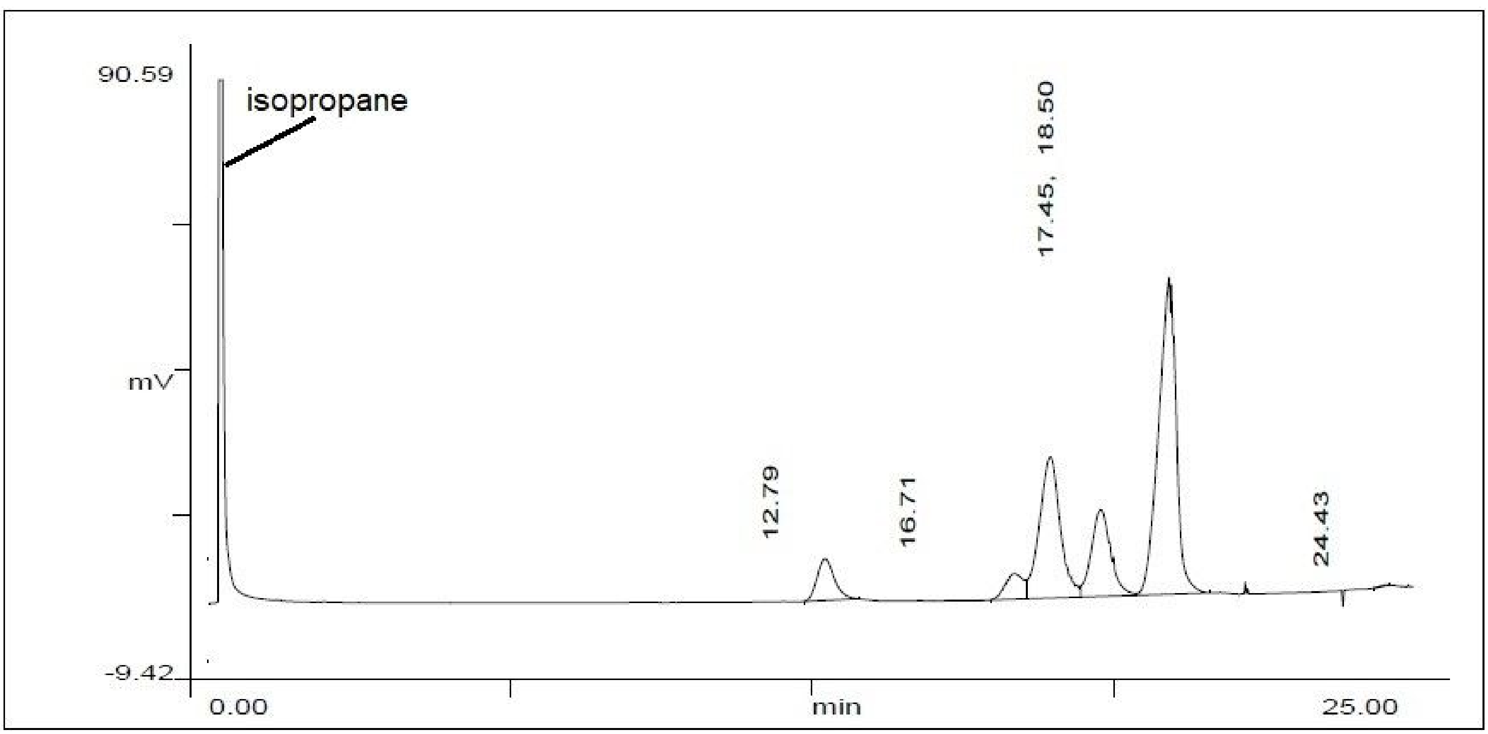

Figure 10

Gas chromatogram for linseed methyl ester (LSME)