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Application of the Box-Behnken Design for Optimizing Biodiesel Output from Castor Oil: Analysis and Characterization

Sheyda Rezaei[1], Seyed Saeid Mohtasebi[1]✉, Barat Ghobadian[2], Behzad Nouri [3], Majid Namdari[4]

[1] Department of Agricultural Machinery Engineering, Faculty of Agricultural Engineering and Technology, College of Agriculture & Natural Resources, University of Tehran, Karaj, Iran.
[2] Department of Mechanical Engineering, Tarbiat Modares University, Jalal ale Ahmad highway, Tehran, Iran.
[3] College of Food Science and Biotechnology, Zhejiang Gongshang University, Hangzhou, 310018, China.
[4] Department of Plant Production and Genetics, Faculty of Agriculture, University of Zanjan, Zanjan, Iran.

✉ Corresponding author: mohtaseb@ut.ac.ir

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ABSTRACT

This study specifically examines the process of producing and analyzing biodiesel made from castor oil using base-catalyzed transesterification. The catalyst used in this process is potassium hydroxide (KOH), and the methanol (CH_3OH) used has a purity of 99.9%. The biodiesel obtained was analyzed extensively to assess its quality. The characterization techniques employed were Gas Chromatography (GC) for compositional analysis, Flash Point measurement for safety assessment, Kinematic Viscosity evaluation for flow properties, and Density determination for mass-volume relationships. To perform a statistical analysis, the Response Surface Method (RSM) was employed to determine the optimal conditions that would yield the highest rate of biodiesel production among the potential solutions. This study focused on three key variables affecting the transesterification process: ultrasonic duty cycle (using a 24 kHz ultrasonic method varying the duty cycle from 20% to 100%), ultrasonic amplitude (varying from 20% to 100%), and reaction time (spanning from 10 to 15 minutes). This investigation achieved a biodiesel yield of 88.38% using a 60% ultrasonic amplitude, a single ultrasonic cycle, and a 15-minute reaction time. The regression model developed can be used to predict biodiesel's percentage conversion.

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INTRODUCTION

Due to growing concerns about global climate conditions, many regions worldwide actively strive to replace non-renewable resources with renewable alternatives (Akia et al., 2014; Rajaeifar et al., 2015). Among the sustainable resources, biofuels stand out as a significant alternative to fossil fuels. The use of biofuels, such as biodiesel derived from the transesterification of vegetable oils or animal fats, has seen a substantial rise on a global scale. Biofuels offer several advantages over conventional fossil fuels, as they are biodegradable, environmentally friendly, and sourced from renewable materials (Hill et al., 2006). Additionally, research, such as that conducted by Valente et al., suggests that biofuels can serve as clean energy sources in engines (Valente et al., 2011). Biodiesel plays a pivotal role in environmental conservation, owing to its renewability, and non-toxic nature, alongside its capacity to reduce the carbon footprint, sulfur oxide emissions, and greenhouse gases (Chuah et al., 2016).

The source of biodiesel should not compete with human food sources. Furthermore, it's preferable to produce biodiesel from cost-effective feedstocks (A Shirazi et al., 2014; Rajaeifar et al., 2013). Consequently, waste cooking oil and non-edible oils like Jatropha, Karanja, Nagchampa, and Castor seeds emerge as viable sources for efficient biodiesel production (Gole & Gogate, 2012a, 2012b). Recent trends have shifted toward the utilization of waste resources as alternative feedstocks, specifically emphasizing non-edible plant-based oils as second-generation feedstocks for diverse applications (Manaf et al., 2019). Vegetable oils mainly consist of triglycerides. However, their high viscosity poses a challenge for use in engines, which can be mitigated by esterification, ultimately preparing these oils for the transesterification process (Krohn et al., 2011).

The transesterification process in vegetable oils involves three steps. First, triglycerides are converted into diglycerides. Subsequently, the diglycerides react with alcohol, leading to their conversion into monoglycerides. Finally, the monoglycerides react with alcohol to produce glycerol (Beetul et al., 2014; Vicente et al., 2007). Each step involves the use of one mole of alcohol to yield one mole of ester (Issariyakul & Dalai, 2014). Catalysts employed in the transesterification process fall into two categories: acidic and alkali catalysts. Based on previous research, alkali catalysts are purer and find wider applications (Encinar et al., 2012; Valente et al., 2011). They also tend to be more efficient and cost-effective than acidic catalysts (Moser, 2009).

Castor seeds, scientifically known as Ricinus communis L., contain around 48% oil, primarily rich in ricinoleic acid (Ataei et al., 2022). The majority of castor oil comprises approximately 80-90% ricinoleic acid, followed by 3-6% linoleic acid. Oleic acid and saturated fatty acids constitute smaller portions, around 2-4% and 1-5% respectively (Kılıç et al., 2013). Another advantage of castor seeds is their high oil yield, averaging about 1188 kg per hectare annually (Gui et al., 2008). However, castor oil's higher viscosity than other vegetable oils is due to its molecular structure, necessitating the saturation of its fatty acids to make it more usable in engines (Talkit et al., 2012). This plant is ideal for cultivation in marginal lands to prevent erosion and desert greening because of its tolerance for unfavorable soil conditions, such as low fertility and poor texture (Ataei et al., 2022).

The majority of Iran's dry and semi-arid regions are ideal for growing this plant, and while preventing erosion in these places, consideration can also be given to the generation of fuel and financial gain from them. Additionally, one can take advantage of the castor plant's benefits in agricultural environments by incorporating it into the farm's production rotation scheme. In addition to disrupting the life cycle of weeds, pests, and illnesses in the area, the rotation of this huge plant also creates an appropriate cover for the soil's surface. By spreading its roots deeply, this cover can enhance soil structure and preserve soil moisture while absorbing the most solar energy

possible. Also, due to the long growing season of castor, the soil surface is protected from erosion due to autumn rains. The oil of this plant is soluble in alcohol, which eliminates the need for heat during the esterification process-one of the stages involved in the production of biodiesel-making it a more economically advantageous biodiesel than biodiesel made from other plants. As a result, significant financial savings are achievable (Conceicao et al., 2007).

Transesterification can be done in a number of ways, including ultrasound, microwave radio waves, alcohol reflux temperature, and alcohol supercritical temperature. The ultrasonic process is now more favorable than other transesterification techniques because to recent advancements in this technology (Ramachandran et al., 2013). Based on the research, the ultrasonic approach yields the maximum degree of performance when compared to other methods, with half the energy required in the supercritical methanol method. Additionally, the procedure takes less time to complete (Stavarache et al., 2007). In recent years, the application of ultrasonic cavitation has significantly enhanced the efficiency of biodiesel production processes, ultrasonic cavitation improves mass and heat transfer among immiscible reactants, thereby accelerating the chemical reaction rates. This technology reduces the reaction time and diminishes energy consumption and operating costs compared to traditional mechanical stirring methods (Chuah et al., 2022). Prior research indicates that the ultrasonic technique can cut the reaction time by 10–40 minutes and the amount of catalyst needed by two-three times (Gogate & Kabadi, 2009). Traditional transesterification methods are often time and energy-intensive (Gole & Gogate, 2012a; Rajaeifar et al., 2013). In contrast, transesterification using ultrasonic power proves more efficient, offering faster reactions and reduced energy consumption. This process also lowers the reaction temperature and accelerates the transesterification rate. Prior research indicates that producing biodiesel through low-frequency ultrasound waves (20–50 kHz) is more effective than using high-frequency waves (Choedkiatsakul et al., 2014).

Response Surface Methodology (RSM), which encompasses both Central Composite Design (CCD) and Box-Behnken Design (BBD), are statistical and mathematical techniques used to optimize the effects of various independent parameters on process outcomes (Tamandani & Hashemi, 2022). The Box-Behnken design was selected for our study primarily due to its efficiency in scenarios that do not necessitate extreme factor levels, circumventing unrealistic experimental conditions. This design also requires fewer runs than the Central Composite Design, offering significant time and cost savings for resource-constrained studies. Moreover, it ensures consistent precision throughout the experimental range, essential for reliable and stable test conditions (Das & Mishra, 2017).

In this study, biodiesel was produced from castor seeds through a pressing method to extract castor oil, chosen for its efficiency over hexane oil extraction (Martín et al., 2010). Transesterification was carried out using an Ultrasonic processor, varying parameters like time, amplitude, and cycle. Subsequently, various properties of the resulting fuel, such as viscosity, flash point, and density, were measured using different instruments.

MATERIALS AND METHODS

Chemical Compounds Utilized in the Experiment

Castor oil was collected from Castor beans at a research farm near Tehran, Iran. Similar articles frequently use surveys or interviews with farmers and agricultural service providers engaged in the cultivation of the target crop to gather research data.

All of the data used in this study came directly from the two years of consecutive castor plant cultivation (2012–2013) in Varamin city (south-east of the Tehran province), due to the small area under castor cultivation and the authors' decision to identify and introduce this plant to the area.

Dumarten's classification places this region at latitude 35 degrees 19 minutes 30 seconds north and longitude 51 degrees 39 minutes east. It also has a dry climate and is located 915 meters above the Persian Gulf's average water level. One of the most fertile ecotypes found in the nation, the Mousavi ecotype, provided the seeds used in this study. Every year, 2000 square meters were cultivated.

Before being oiled, the castor seeds that were harvested from the field must be removed from their tough outer layer using a peeling machine. A peeling machine manufactured by Tarbiat Modares University's Department of Biosystems was utilized to detach the seed's skin.

For oilseeds, there are primarily two oiling techniques. This study was conducted because the second method—using an oil extraction machine to extract castor seeds under pressure—is more efficient than the first method, which involves using a solvent. The Tarbiat Modares University Renewable Energy Laboratory is where the oil extraction machine is located (Martín et al., 2010).

Vegetable oils have limited volatility, create carbon deposition in the fuel inlet of diesel engines, and have viscosities 11–17 times higher than biodiesel, hence they cannot be utilized directly in diesel engines. To address these issues, the researchers suggested using the transesterification reaction (Abbaspour Aghdam et al., 2018).

Alcohol and oil react in the presence of a catalyst during the transesterification event. The transesterification synthesis uses methanol, ethanol, butanol, and propanol as alcohols; methanol is the most common and effective type (Hossain et al., 2010; Micic et al., 2014).

Methanol (CH3OH), with a purity of 99.9%, and potassium hydroxide (KOH), with a purity of 99%, were employed as catalysts.

A Detailed Look at Base-Catalyzed Transesterification Using Castor Bean Oil

In the base-catalyzed transesterification process utilized for this study, potassium hydroxide (KOH) is dissolved in high-purity methanol to create a catalyst solution. This solution is then thoroughly mixed with castor bean oil, which serves as the lipid feedstock, under controlled conditions maintained at 60-65°C. The resultant mixture undergoes a transesterification reaction where the triglycerides in the castor bean oil are converted into methyl esters (biodiesel) and glycerol. Following the reaction, the mixture is allowed to settle, enabling the biodiesel to separate from glycerol. The biodiesel is then purified through water washing to remove residual KOH, methanol, and glycerol, followed by drying. Finally, the quality of the biodiesel is assessed based on key parameters like viscosity, density, flash point, and ester content to ensure compliance with fuel standards.

Method for Estimating Free Fatty Acids in Produced Castor Oil

The calculation was based on the maximum fatty acid content (primarily oleic acid) to determine the amount of free fatty acids in Castor oil. This was achieved by mixing around one cc of oil with 10 ml of Propane alcohol and adding three drops of Phenolphthalein as an indicator. Gradually adding an alcoholic solution of potassium hydroxide (with a density of 0.1 mol /L) changed the solution's color to purple. The percentage of free fatty acids was then calculated using Equation (1) (Gerpen et al., 2004), yielding 1.5% in this study. Since this value was below the standard limit of 7%, there was no need for a prior esterification reaction before entering the transesterification process involving oil, alcohol, and catalyst.

$$\%\mathbf{FFA} = \frac{\mathbf{0.5} \times \mathbf{A} \times \mathbf{N} \times \mathbf{W}}{\boldsymbol{W}_{\mathbf{cat}}} \quad (1)$$

In Equation (1), A represents the required amount of catalyst for oil titrations in milliliters, W is the amount of oil sample in grams, N is the normality (equal to 0.1) and W_{cat} is the molecular mass of the catalyst (56.1 g for potassium hydroxide).

Molar Ratio of Alcohol to Oil

Based on prior studies [13], an alcohol-to-oil molar ratio of 9:1 was chosen, as it enhances methyl ester yield, reaction rate, and reduces processing time.

Transesterification Reaction in the Reactor

Nowadays, biodiesel is the primary product of the ultrasonic technique. Both the kinetic energy needed to initiate the transesterification process and the mechanical (hydrodynamic) energy for the combination are provided by the high frequency wave that ultrasound produces in comparison to the human hearing range.

Before initiating the process, potassium hydroxide and methanol were mixed using a magnetic stirrer to enhance dissolution. An ultrasonic source with a power of up to 400 watts and a constant frequency of 24 kHz was used. Different amplitude and duty cycle settings were applied to the sample. The temperature of Castor oil was raised to 33°C in an oven before introducing it into the reactor. To maintain a consistent temperature during the experiment, samples were placed in a water bath at 40°C, followed by the addition of methoxide solution. The ultrasonic process commenced with predefined values for time, cycle, and amplitude. After completing the transesterification reaction, the compound was centrifuged for 30 minutes at 2500 rpm. Gas chromatography (GC) was used to determine the fatty acids profile, analyze fuel constituents, and measure the conversion percentage of biodiesel from Castor oil.

Gas Chromatography Analysis of Biodiesel Samples

Gas chromatography (GC) was employed to analyze the biodiesel samples using a PerkinElmer – Clarus 580 system from the USA, adhering to the BS EN 14103 standard. The GC included a capillary column (30 m × 0.32 mm × 0.25 μm) and a flame ionization detector (FID). The air-to-hydrogen flow rate ratio was 450/45. Helium with 99.99% purity served as the carrier gas at a flow rate of 1.5 mL/min. Heptane was used as a solvent. The detector, injector, and sample injection site were set at 250°C. The split ratio was 100 mL/min, and the sample injection volume was 0.5 μL. The temperature ramp program started at 60°C for 2 minutes, then increased by 10°C/min to 200°C, and finally reached 240°C at a rate of 5°C/min for 7 minutes.

Response Surface Methodology

After completing the experiments, the Design Expert software (Version 7.0.0, StatEase, Inc., USA) was used for detailed data analysis and to find optimum points. A Box-Behnken design with 3 factors at 3 levels each was used to assess the impact of time, cycle, and amplitude on fuel conversion from the oil. Coded and actual levels of independent variables are provided in Table 1. The software designed 17 experiments with varying independent variable values. Equation (2) was employed to establish the effects of variables on yield and energy:

$$y = \beta_0 + \sum_{j=1}^{q} \beta_j X_j + \sum_{I=1}^{q} \beta_{jj} X_j^2 + \sum_{i} \sum_{i<j} \beta_{ij} X_i X_j + \mathcal{E} \quad (2)$$

Where y is the response, β_0 is a constant coefficient, Xi and Xj are independent variables, q is the number of independent factors, $\mathcal{E}$ is the error, and βj, βjj, and βij are coefficients of linear, quadratic, and interaction effects respectively.

Table 1. Actual values and ranges of variables used in the experimental design.

Variables Factors		Coded levels		
		-1	0	+1
Time (min)	A	10	12.5	15
Amplitude	B	20	60	100
Cycle	C	0.2	0.6	1

Ultimately, the process's ideal point was identified by selecting the right weights and range of modifications based on the experiment, and its value was verified by repeating the experiment at the recommended point.

RESULTS AND DISCUSSION

The fatty acid composition of Castor oil is outlined in Table 2.

Table 2. The level of fatty acids in the Castor oil

Fatty acids in the Castor oil	Systemic name	Value
Palmitic	Hexadecanoic	2.08
Stearic	Octadecanoic	1.09
Oleic	9-Octadecenoic	5.57
Linoleic	9,12-Octadecadienoic	6.77
Ricinoleic	2-hydroxy-9-Octadecenoic	81.55
Saturated fatty acids	-	3.17
Unsaturated fatty acids	-	93.89

Experimental Design

The yield results for biodiesel samples are presented in Table 3. The regression model used to predict yield based on different variable values is described by Equation (3).

$$\text{Yield} = 73.77 + 5.35 \times A + 2.51 \times B + 3.20 \times C + 1.73 \times A \times B + 1.17 \times A \times C + 0.44 \times B \times C - 0.94 \times A^2 + 1.03 \times B^2 + 5.82 \times C^2 \quad (3)$$

In this case, A stands for time, B for amplitude, and C for cycle. The synergistic effect of the parameter(s) on the response is indicated by the positive sign in front of each sentence, while the negative sign shows the opposite effect.

Table 3. Experimental conditions and results for the ultrasonic-assisted biodiesel production process.

Run	A Time (min)	B Amplitude (%)	C Cycle	Yield (%)
1	12.5	60	0.6	69.84
2	10	20	0.6	67.78
3	12.5	100	0.2	78.82
4	12.5	60	0.6	72.02
5	15	20	0.6	74.27
6	12.5	20	0.2	75.30
7	15	100	0.6	83.37
8	12.5	60	0.6	69.84
9	12.5	100	1	86.79
10	15	60	0.2	80.34
11	10	60	1	74.59
12	12.5	60	0.6	81.33
13	12.5	20	1	81.51
14	12.5	60	0.6	75.79
15	10	60	0.2	71.22
16	15	60	1	88.38
17	10	100	0.6	69.96

The regression exhibited significance at a 95% confidence level. Model evaluation included the determination of the correlation coefficient (R), adjusted determination coefficient (R2a), and coefficient of variance (CV). With a coefficient of determination (R2) of 0.844, only 0.156 of the total variation remained unexplained by the model. A coefficient of variance of 4.89% indicates a favorable correlation between experimental and predicted data. The ANOVA details for the model can be found in Table 4.

Table 4. Analysis of variance (ANOVA) for the percentage of biodiesel conversion in a quadratic regression model

Source of variation	Degrees of freedom	Sum of squares	Mean squares	P-value
Model	9	530.93	58.99	0.03*
Time	1	229.10	229.10	0.004**
Amplitude	1	50.39	50.39	0.09 ^{ns}
Cycle	1	82.01	82.01	0.04*
Time× Amplitude	1	11.99	11.99	0.3 ^{ns}
Time × Cycle	1	5.43	5.43	0.5 ^{ns}
Amplitude × Cycle	1	0.77	0.77	0.8 ^{ns}
Time × Time	1	3.76	3.76	0.6 ^{ns}
Amplitude × Amplitude	1	4.45	4.45	0.5 ^{ns}
Cycle ×Cycle	1	142.38	142.38	0.01*
residuals	5	98.00	14.00	
Lak of fit	3	2.86	0.95	0.9 ^{ns}
Pure error	2	95.14	23.78	
Total	14	628.93	-	

* and ** denote effects significant at 5 and 1 percent probability level respectively; ns denotes effects no significant (ns)

Table 4. utilized a Box-Behnken design within Response Surface Methodology to optimize biodiesel production from castor oil, achieving a significant model with an F-value of 58.99 and a p-value of 0.03, indicating robust predictive capability. Notable were the significance of the Time, Cycle, and the quadratic effect of Cycle, with p-values of 0.004, 0.04, and 0.01 respectively, highlighting their influence on the process efficiency. Amplitude and several interaction terms showed no significant effect, suggesting potential for model simplification. Importantly, the Lack of Fit was non-significant (p-value = 0.9), confirming the model's adequacy in fitting the experimental data. This optimization not only underscores the effectiveness of ultrasonic-assisted transesterification but also enhances the economic feasibility of biodiesel production by identifying key operational parameters, thereby contributing significantly to sustainable biofuel development.

Overall Comparison Based on Model Terms

Figure 1 illustrates a comparison between actual and predicted biodiesel production (BP) outputs. The close alignment between experimental and predicted values signifies the model's high reliability and its good fit to the experimental data.

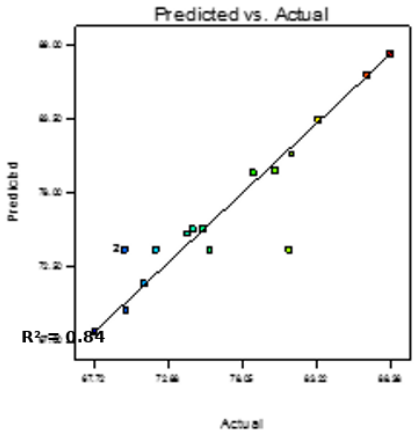

Figure 1. A comparison between experimental and predicted values for biodiesel production from castor oil

Figure 2 (not visible here) displays the effects of time, pulse, and amplitude on performance. Observing the figure, biodiesel production steadily increases with rising time and amplitude. Notably, the effect of amplitude at lower values is more pronounced than that of time. While biodiesel production decreases initially with increasing pulses, it exhibits an upward trend with higher pulse values.

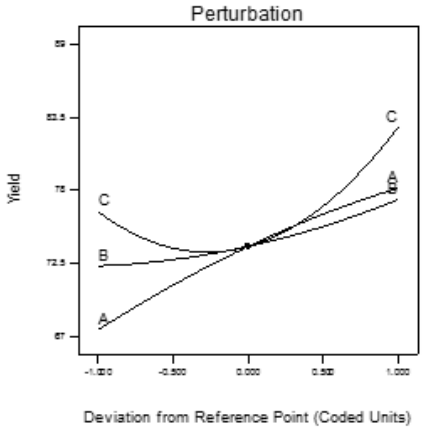

Figure 2. Effect of time(A), amplitude (B) and pulse (C) on PB (%) yield.

Effects of Different Variables

Three-dimensional response surface graphs illustrate the impact of independent variables on biodiesel production. Each figure displays the effect of two variables on yield. For instance, Figure 3 depicts the simultaneous effects of time and amplitude on biodiesel production. It reveals that, for all amplitude values, an increase in time corresponds to improved performance. The influence of amplitude at the minimum time (10 minutes) is insignificant. However, at lower amplitudes (20), increased time leads to higher yields. The peak yield is achieved at 15 minutes and an amplitude of 100. Yield notably rises with just a 5-minute extension in time.

Figure 4 showcases a yield decrease with increasing pulse up to 60, after which it experiences a significant increase. Across all three pulse values, there's a gradual increase with rising time. This trend is most pronounced at 30 minutes and pulse 1, where yield reaches up to 89%. Figure 5 illustrates that, across all pulses, higher amplitudes correspond to increased biodiesel production. The highest efficiency of around 87% is achieved with a pulse value of 1 and an amplitude of 100.

Graph-Based Overall Discussion

The remaining diagrams in Figure 6 (not visible here) assess the model. Figure 6a shows a random scatter of residuals around the zero line. In contrast, Figure 6b indicates that the graph lacks a discernible pattern, suggesting a constant value for residual variance without a clear connection between observations and residuals.

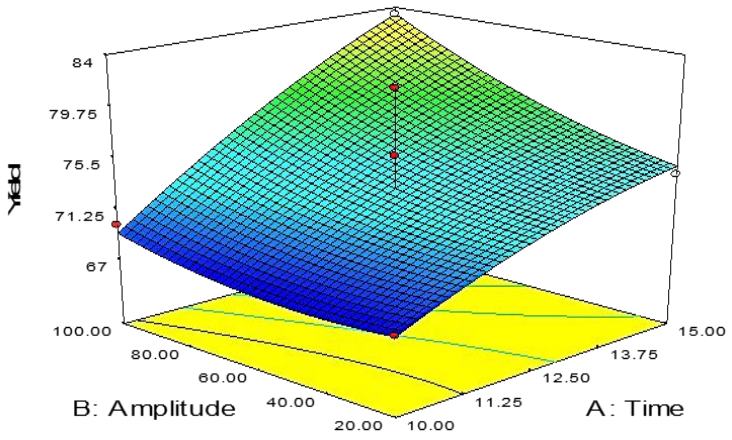

Figure 3. Biodiesel yield versus amplitude and reaction time.

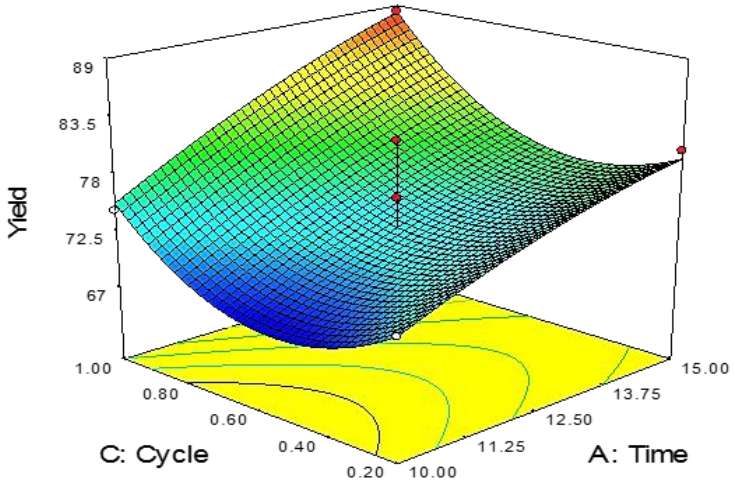

Figure 4. Biodiesel yield versus pulse and reaction time**.**

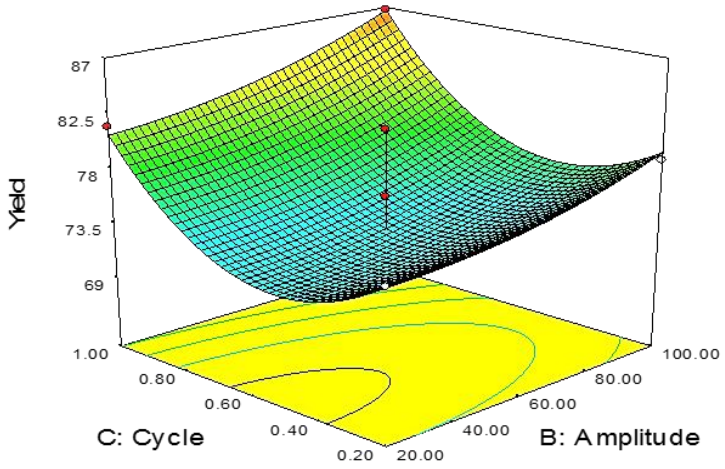

Figure 5. Biodiesel yield versus amplitude and pulse

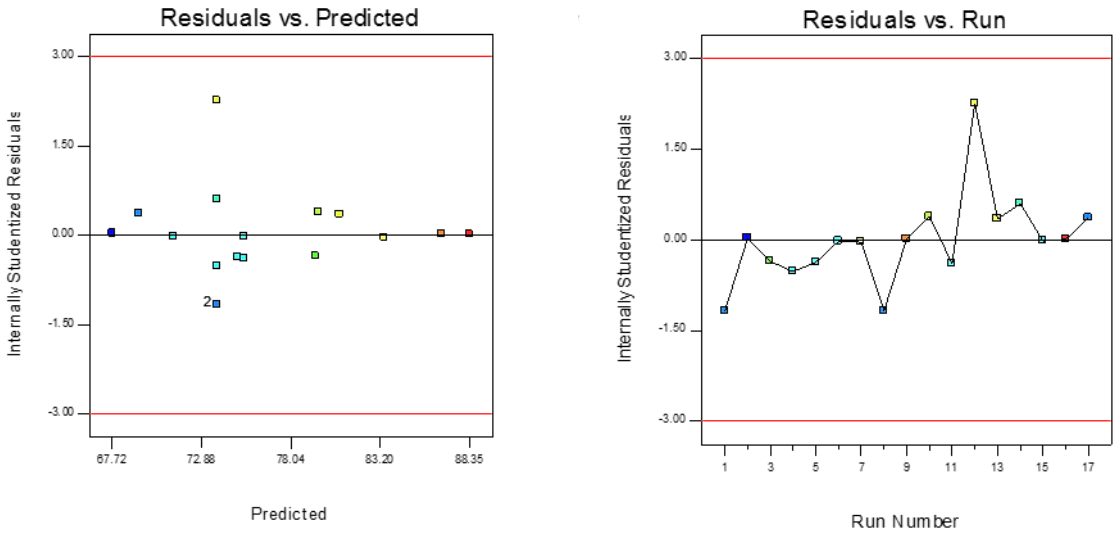

Figure 6. Parity plots between the residuals and predicted data of the biodiesel yield in the ultrasonic-assisted biodiesel production process.

Process Optimization

Optimization involved an interplay between three key parameters (time, amplitude, and cycle) to attain the highest yield. Response for each variable was optimized within their respective surface limits. The optimal input variable values are detailed in Table 5. The characteristics and combustion modeling of the produced fuel were determined using its physical properties, as listed in Table 6.

Table 5. Optimized conditions suggested by the Design Expert software

	Value		Value
Time	12.16	95% CI low	69.7
Amplitude	46.01	95% CI high	80.7
Cycle	0.21	95% Pl low	64
Predicted yield	75.08	95% Pl high	83.4
Standard error mean	2.2	Standard error predicted	4.3

CI: confidence interval, PI: prediction interval

Table 6. Physicochemical properties of PB.

Tests	Range	ASTM
Flash point	181.2-194.1	D6450 & D7094 & D93/ISO 2719
Kinematic viscosity(mm^2/s)	5.9805-6.9913	D7042-04 & D445
Density (g/cm^3)	0.8938-0.9056	D7042-04 & D445

The study by Sáez-Bastante et al. (2015) on biodiesel production from castor oil using ultrasound-assisted transesterification demonstrates significant advantages over conventional methods. Ultrasound application led to higher castor oil methyl ester (COME) yields of 86.57% under optimized conditions,

with reduced reaction times and lower energy consumption, compared to conventional transesterification which achieved only 54.1% yield.

The study by Choedkiatsakul et al. (2014) on biodiesel production from palm oil using a combined mechanical stirred and ultrasonic reactor achieved substantial yields and demonstrated efficient process intensification, reporting an initial reaction rate up to 164.2 mmol/L min and a biodiesel yield of 76% at the reactor outlet within 5 minutes. This rapid achievement showcases the effectiveness of integrating mechanical stirring with ultrasonic cavitational effects, significantly accelerating the transesterification process compared to traditional methods. The present study complements these findings by employing statistical optimization through a Box-Behnken design, providing a robust analytical framework that emphasizes the impact of key variables such as time, cycle, and amplitude on process efficiency. In the study by Siaw et al. (2023) biodiesel production using a hybrid of mechanical stirring and high-frequency ultrasound achieved a conversion rate of 89%. This method significantly improved the transesterification reaction by enhancing reactant miscibility and contact, thus optimizing conversion efficiency. These findings align with the current research, demonstrating the critical role of ultrasonic energy in enhancing biodiesel yield and emphasizing the efficacy of combined mixing technologies in biofuel production. The study by Supriyadi et al. (2018) on biodiesel production from Kemiri Sunan oil using ultrasonics achieved a significant 88% conversion rate, emphasizing ultrasonic energy's efficiency in enhancing transesterification and reducing process time, resonating with current research findings that highlight the effectiveness of optimized ultrasonic parameters in improving biodiesel yields. The study by Pal and Kachhwaha (2013) on biodiesel production using ultrasonic cavitation from waste cooking oil achieved an impressive yield using low-frequency ultrasonic energy (28-33 kHz). They observed that ultrasound energy considerably shortened reaction times and improved biodiesel yield compared to conventional methods.

CONCLUSIONS

The optimization of three key parameters in the transesterification reaction of castor oil was explored, employing ultrasonic parameters such as cycle (ranging from 0.2 to 1), time (varying from 12.5 to 1 minute), and amplitude (spanning from 20% to 100%). Response Surface Method (RSM) was applied to maximize biodiesel yield. Notably, there's a strong agreement between the predicted values and the experimental data, as indicated by an R-squared value of 0.84. Through our experimentation, we achieved a 75% output by utilizing the following parameter values: 12.16 minutes for time, 46.01 for amplitude, and 0.21 for cycle. These outcomes underscore the effectiveness of the model for enhancing biodiesel production.

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