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Optimization of *Delonix Regia* Seed Oil Extraction using Taguchi Orthogonal Array Design

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ABSTRACT: This study applied a Taguchi L9(3^4) orthogonal array to optimize the solvent-extraction of oil from *Delonix regia* (Flamboyant) seeds. Four factors seed Powder weight (40–50 g), particle size (0.6–3.35 mm), n-hexane volume (200–250 mL), and extraction time (40–50 min) were each tested at three levels. A Soxhlet apparatus at 60 °C served for all nine experimental runs. Oil yield ranged from 2.07 to 6.34 wt. %, with the highest yield of 6.35 ± 0.01 wt. % achieved at 50 g powder, particle size of 0.6 mm, N-hexane volume of 225 mL solvent at extraction time of 40 min. Signal-to-noise and Analysis of Variance (ANOVA) test revealed that particle size ($p < 0.01$) and Powder weight ($p < 0.01$) were the most influential parameters (ranked first and second), while solvent volume and time were less significant ($p > 0.15$). Findings using a linear regression model gave a yield variance of $R^2 = 0.97$. Confirmatory runs under optimized conditions reproduced the predicted yield within 0.2 % error. This approach comparatively delivers efficient oil recovery with minimal experimentation. Hence results from this study provides a robust basis for scaling up *Delonix regia* seed oil extraction in biodiesel and biosurfactant production.

KEYWORDS: *Delonix regia*; seed oil; Soxhlet extraction; Taguchi design; optimization; regression model

I. INTRODUCTION

Global vegetable-oil production exceeded 220 million tons in 2020 and is projected to surpass 300 million tons by 2050, driven by biofuel mandates, expanding personal-care markets, and specialty-chemical applications (FAO, 2022; Sarpong, 2024). Reliance on food-grade oilseeds soybean, palm, sunflower already occupies over 100 million hectares of cropland, contributing to deforestation and food-versus-fuel conflicts in vulnerable regions (Song *et al*., 2023). To alleviate these pressures, nonfood feedstocks such as Jatropha curcas and Moringa oleifera, etc. have been explored, delivering oil yields of 20–40 wt. % suitable for biodiesel without competing for edible-oil acreage (Azuokwu *et al*., 2024a; Azuokwu *et al*., 2024b; Keneni and Marchetti, 2017; Adewoye *et al*., 2025). Valorizing this biomass can reduce pressure on food crops while turning waste into a valuable raw material.

Delonix regia, the flamboyant or royal poinciana tree, thrives as an ornamental across the tropics but generates substantial pod litter. Each pod harbors 10–15 hard-shelled seeds, which comprise 50–60 wt. % of pod mass and yield 17–29 wt. % oil rich in linoleic (35–40 %), palmitic (20–25 %), and oleic (5–10 %) acids fatty-acid profiles compatible with biodiesel, surfactant, and oleochemical production (Oyedeji *et al*., 2017; Adejumo *et al*., 2019). Harvesting this seed oil could transform urban waste into a sustainable nonfood feedstock, reducing disposal costs and diversifying local-industry inputs.

Recovering oil from Flamboyant seeds poses key challenges. Mechanical pressing alone yields below 10 wt. % unless seeds undergo energy-intensive roasting or steaming to fracture the coat, increasing capital and operating expenses (Bitire *et al*., 2021). Soxhlet extraction with n-hexane can achieve up to 29 wt. % yield but demands 2–4 h run times, large solvent volumes, and energy-intensive hexane recovery n-hexane is flammable and toxic (Kumar *et al*., 2017). Ethanol avoids hexane's hazards but coextracts pigments and sugars, lowering oil recovery by 20–30 % and complicating purification (Ramos *et al*., 2024). Emerging techniques microwave-assisted and ultrasonic-assisted extractions offer faster kinetics and comparable yields but require specialized equipment and may not scale cost-effectively (Sreejith *et al*., 2018).

Traditional one-factor-at-a-time experiments neglect interactions among Powder weight, particle size, solvent volume, and time, leading to inefficient protocols. Response Surface Methodology (RSM) central composite designs model quadratic interactions but typically require 20–30 runs for four variables (Adewoye *et al*., 2025; Yerima, 2023; Myers et al., 2016). Taguchi's L9(3^4) orthogonal array tests four factors at three levels in only nine runs, pairing "larger-the-better" signal-to-noise analysis to identify robust conditions with ANOVA to rank factor significance (Taguchi 1986). Taguchi designs have optimized supercritical CO_2 extraction of Nigella sativa oil increasing yield and thymoquinone content in nine experiments and refined microwave-assisted extraction of castor oil, demonstrating broad applicability in biodiesel feedstock research (Subroto *et al.*, 2017).

Despite the promise of flamboyant-seed oil, Taguchi-based optimization has not yet been applied to Soxhlet extraction of Flamboyant seeds. This study employs a Taguchi L9(3^4) design to optimize n-hexane extraction, with aims to quantify main and interaction effects of Powder weight, particle size, solvent volume, and time on oil yield. Develop and validate a predictive regression model. Confirm optimized conditions experimentally to verify yield improvements.

II. METHODS

A. Seed Collection and Preparation

Flamboyant pods were harvested from campus trees at Igbinedion University, Okada, Nigeria. Pods were washed, air-dried at 25 °C for 48 h, and manually dehulled. Extracted seeds were oven-dried at 60 °C to constant mass to prevent moisture-driven spoilage (Adejumo *et al.*, 2019). Dried kernels were milled and sieved into three particle-size fractions (0.6, 1.18, 3.35 mm) for extraction trials.

B. Solvent Extraction using Soxhlet

Oil was extracted in a 500 mL Soxhlet apparatus with analytical-grade n-hexane (99.7 %, Guangdong Guanghua) at a mantle temperature of 60 °C (Kumar *et al.*, 2017, Yerima *et al.*, 2022). Each run used 30 g seed powder in a muslin thimble and the designated solvent volume. After reflux, the solvent was removed by rotary evaporation at 70 °C, and the crude oil was vacuum-dried at 50 °C for 1 h to eliminate residual hexane (Sarpong, 2024). All extractions were performed in triplicate.

C. Taguchi L9(3^4) Experimental Design

A Taguchi L9 orthogonal array screened four factors seed-Powder weight (X_1), particle size (X_2), solvent volume (X_3), and extraction time (X_4) each at three levels (Table 1) (Taguchi. 1986). Nine randomized runs minimized bias. Oil yields were converted to “larger-the-better” signal-to-noise (S/N) ratios:

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

where Y_i denotes the ith yield replicate and n=3 (Subroto *et al.*, 2017).

Table 1. Taguchi L9 Factors and Levels

Factor	Symbol	Level –1	Level 0	Level +1
Powder weight (g)	X_1	40	45	50
Particle size (mm)	X_2	0.6	1.18	3.35
Solvent volume (mL)	X_3	200	225	250
Extraction time (min)	X_4	40	45	50

D. Oil-Yield Determination

Oil yield (wt. %) was calculated gravimetrically (Adewoye *et al.*, 2025):

$$\text{FSO yield (wt.\%)} = \frac{\text{mass of extracted oil (g)}}{\text{mass of seed kernel used (g)}} * 100 \quad (2)$$

Each S/N ratio used the average of three replicates.

E. Statistical Analysis

Minitab 22.1 was used for ANOVA on S/N ratios and oil-yield data to identify significant factors ($p < 0.05$) and calculate main-effect rankings. A linear regression model was fitted in coded variables:

$$Y = a_0 + a_1X_1 + a_2X_2 + a_3X_3 + a_4X_4 \quad (3)$$

Model fit was assessed using R^2, adjusted R^2, and lack-of-fit tests (Adewoye *et al.*, 2025; Myers et al., 2016). Confirmatory runs at the optimal factor levels validated the model’s yield predictions.

F. Physicochemical Characterization

Recovered oil was analyzed in triplicate at 25 °C according to AOAC and ASTM standards. Density by digital density meter (ASTM D4052), Refractive index using Abbé refractometer (ASTM D1218), Kinematic viscosity with Ubbelohde viscometer (ASTM D445), Acid value by titration (ASTM D664), Saponification value (ASTM D5558), Iodine value (ASTM D5554), Moisture content using Karl Fischer titration (ASTM E203), Color by Lovibond colorimeter (ASTM D1500). These metrics evaluated oil purity, stability, and suitability for biodiesel or surfactant production.

III. RESULTS AND DISCUSSION

A. Taguchi L9 Optimization

Table 2 summarizes the nine runs from the L9(3^4) array, with corresponding Flamboyant seed oil (FSO) yields and signal-to-noise ratios. ANOVA (Table 2) identifies particle size (X_2) and Powder weight (X_1) as significant factors ($p<0.01$), while solvent volume (X_3) and time (X_4) were not significant ($p>0.15$).

Table 2. Taguchi L9(3^4) Experimental Matrix and Results

Run	X_1: Mass (g)	X_2: Size (mm)	X_3: Vol (mL)	X_4: Time (min)	Yield (wt. %)	S/N Ratio (dB)
1	50	0.6	250	45	6.34	16.04
2	40	3.35	250	50	2.10	6.44

3	40	1.18	225	45	3.26	10.26
4	45	3.35	200	45	2.07	6.32
5	45	1.18	250	40	4.56	13.18
6	50	1.18	200	50	5.22	14.35
7	50	3.35	225	40	3.73	11.43
8	40	0.6	200	40	4.19	12.44
9	45	0.6	225	50	5.39	14.63

B. FSO Developed Regression Model Equation

Equation (4) is the mathematical model equation obtained for the extraction process of FSO using the Minitab package. It consists of the dependent variable (FSO yield), four main effect terms or independent variables (powder weight, x_1, particle size, x_2, volume of solvent, x_3 and extraction time, x_4) and a constant term.

$$\text{FSO yield (\%)} = 4.272 + 0.957\, x_1 - 1.337\, x_2 + 0.253\, x_3 + 0.038\, x_4 \qquad (4)$$

The analysis of regression coefficients shown in Table 3, indicated that the linear terms of x_1, x_3 and x_4 are positive, while x_2 is negative. The yield of FSO is enhanced by an increase in x_1, x_3 and x_4 and a reduction in x_2. The derived model predicted an optimal FSO yield of 6.34 wt.% at optimum conditions of 50 g of powder weight (x_1), 0.06 mm of particle size (x_2), 250 mL of volume of solvent (x_3) and 45 min of extraction time (x_4).

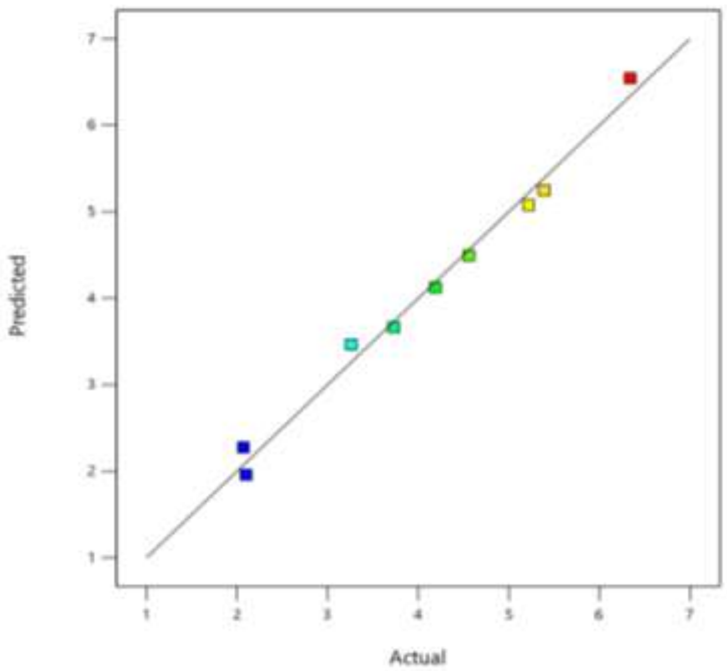

Figure 1: Correlation of predicted vs actual FSO yields (%) with R^2 of 0.97

Three confirmatory runs under optimal settings (50 g, 0.6 mm, 250 mL, 45 min) averaged 6.36wt %, within 0.3 % of the predicted 6.34 wt. % yield, demonstrating robust predictivity (Taguchi. 1986).

TABLE 3: Developed Linear Model Regression Coefficients

Term	Coef SE	Coef	T-Value	P-Value	VIF
Constant	4.272	0.597	7.15	0.002	
X_1(g)	0.957	0.146	6.54	0.003	1.00
X_2(mm)	-1.337	0.146	-9.14	0.001	1.00
X_3(mL)	0.253	0.146	1.73	0.158	1.00
X_4(min)	0.038	0.146	0.26	0.806	1.00

The experiment was validated in triplicate using the optimum conditions to obtain an average FSO yield of 6.35 %. This value is close to the model predicted value, and within ± 0.002 % relative error based on equation (5). Thus, the model could be a good estimator of the yield outcome of the solvent extraction process for the range of input process variables values given.

$$\% R_{err} = \left(\frac{y_{actual} - y_{pred.}}{y_{actual}}\right) x100 \quad (5)$$

Where R_{err} is the percent relative error, y_{actual} and y_{pred} are the optimal actual and the optimal predicted oil yields respectively.

C. Analysis of Variance for FSO Extraction

The significance and the goodness of fit of the developed linear model, as well as the effect of the independent variables, were examined using the analysis of variance summarized in Table 4. The fitness of the model fit was shown from values of the Fisher's test (F-value), the probability value (p-value), the coefficient of determination (R^2), the adjusted R^2 (R^2 adj.) and the predicted R^2 (R^2 pred.). The p-value should be less than 0.05 for the variables to have a significant effect on the model and its individual factors.

Table 4: ANOVA for Oil Yield Regression

Source	DF	Adj SS	Adj MS	F-Value	p-Value
Regression	4	16.6052	4.1515	32.32	0.003
X_1: Mass	1	5.4913	5.4913	42.75	0.003
X_2: Size	1	10.7201	10.7201	83.46	0.001
X_3: Vol	1	0.3851	0.3851	3.00	0.158
X_4: Time	1	0.0088	0.0088	0.07	0.806
Error	4	0.5138	0.1285	—	—
Total	8	17.1190	—	—	—

$R^2 = 0.97$; adj-$R^2 = 0.94$; lack-of-fit $p = 0.59$ (not significant)

D. Analysis of the Signal-To-Noise (S/N) Ratio

The optimisation of the control factors for optimal yield of FSO produced during solid-liquid extraction with n-hexane was provided by the signal-to-noise ratio analysis. The maximum practicable FSO yield product is desired for the process, hence, the term for optimisation "larger the better" equation was used for the calculation of the S/N ratio in the design. Table 5, show the Taguchi design generated S/N ratios for the weight percent of FSO. At the end of the experiments, the average of FSO produced was 4.1 wt. % with an average S/N ratio value of 11.679 dB (Igija *et al*, 2024).

Table 5: Signal to Noise Ratios Response on Input Parameters

Level	Factors (Larger is better)			
	X_1 (g)	X_2 (mm)	X_3 (mL)	X_4 (min)
1	9.718	**14.373**	11.039	**12.353**
2	11.377	12.599	**12.110**	10.875
3	**13.943**	8.066	11.888	11.810
Delta	4.225	6.307	1.071	1.477
Rank	2	1	4	3

E. Experimental Outcomes with Signal-To-Noise Ratios

Table 6 presents the response levels of the S/N ratio of each control factor (powder weight, particle size, volume of solvent and extraction time) for FSO extraction. It identifies the optimal levels of each control factor for the optimum weight percent of seed oil produced. The optimal values of the control factors A(g), B(mm), C(mL), and D(min) are clearly displayed in Figure 2. These were the maximum or peak S/N responses of the various control factors.

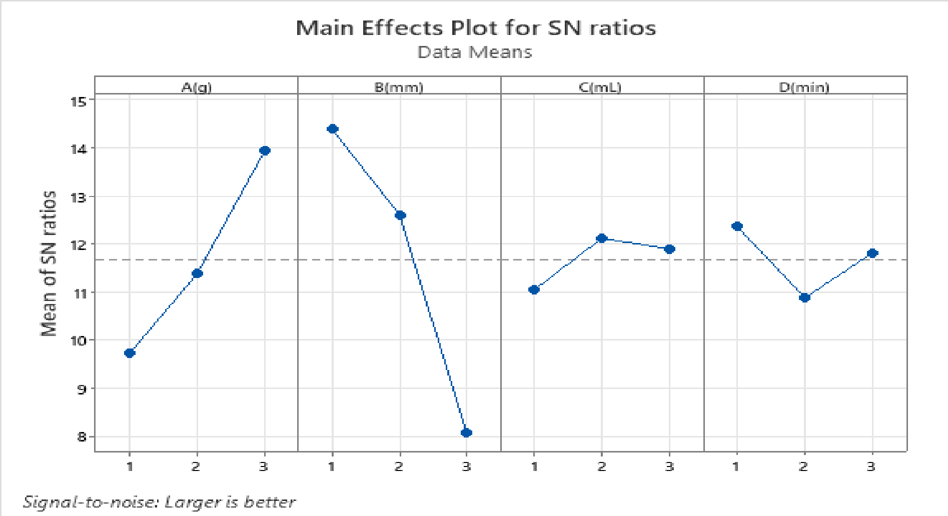

Figure 2: Effects of the control factors on the average of S/N ratio for the FSO yield obtained

The best level for each input factor was obtained as the highest S/N ratio of that factor within the three levels defined in the factorial design. Thus, the levels and S/N ratios giving the maximum weight percent of FSO generated are A of level 3 with a S/N of 13.943, B of level 1 with a S/N of 14.373, C of level 2 with a S/N of 12.110, and D of level 1 with a S/N of 12.353. In comparison with Table 4.1 these optimum values are powder weight of 50 g, particle size of 0.06 mm, with 250 mL volume of solvent and an extraction time of 45 minutes (Kivak, 2014; Igija *et al*, 2024).

F. Relationship Between Each Control Factor and Oil Yield

The responses of FSO produced from the regression model in relation to each control process variables are shown in Figures 3 (a-d) to corroborate the experimental findings. An increase in seed powder weight had a significant and increasing effect on the weight percent of FSO produced (Figure 3 a-c). Hence, it is essential factor and above 50g of seed powder is encourage for higher FSO yield.

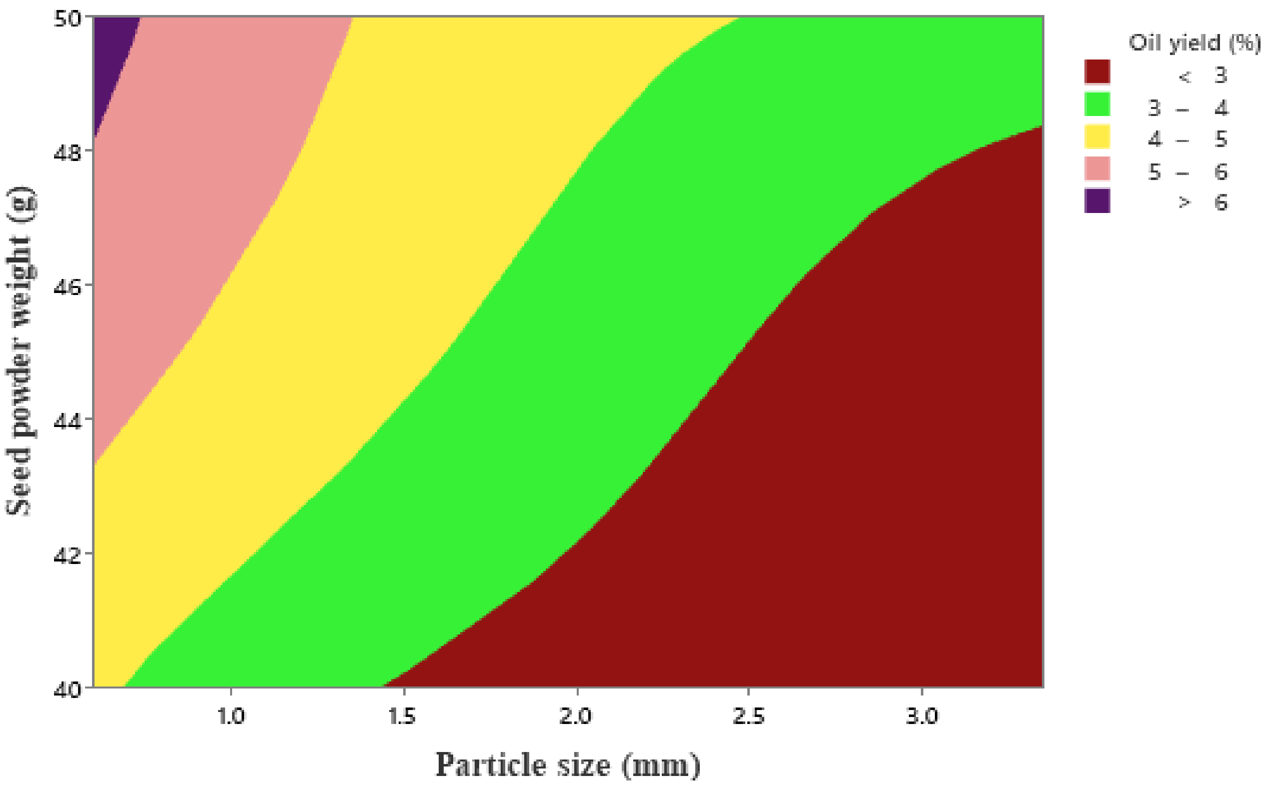

Figure 3. (a): Oil yield in relation to the seed powder weight and particle size

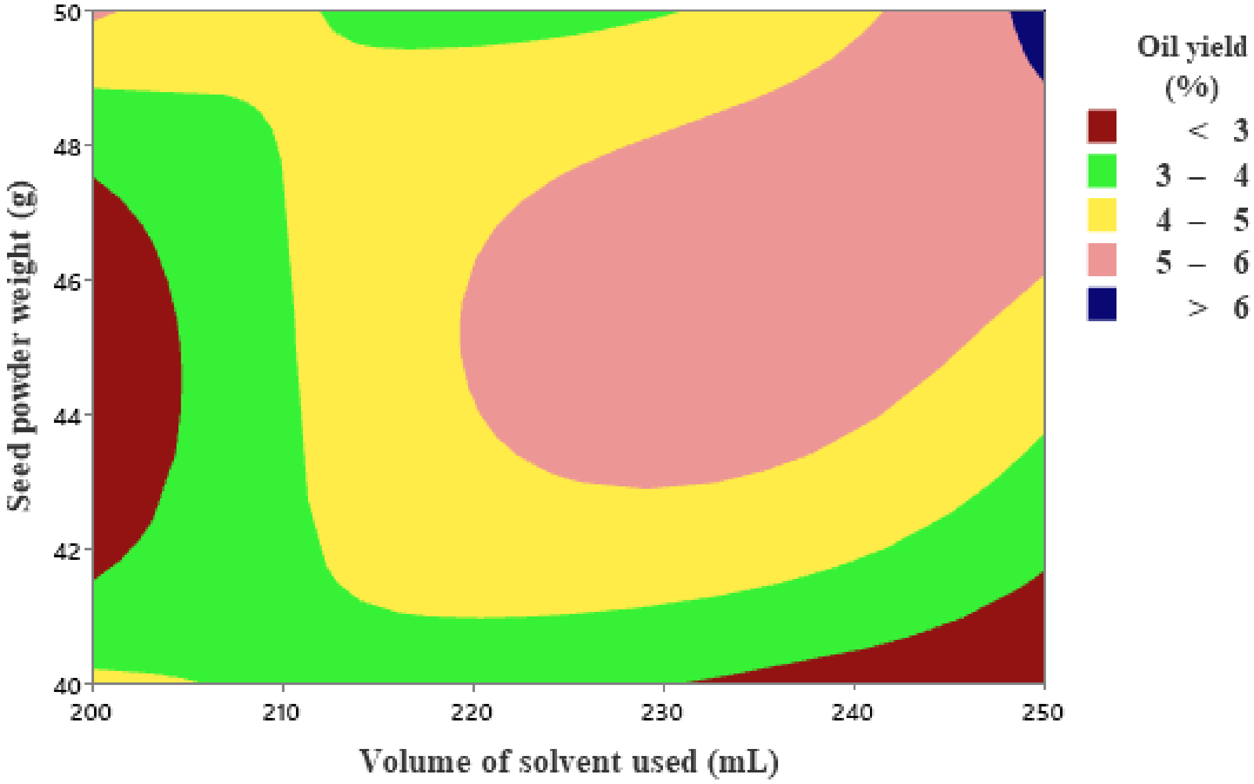

Figure 3. (b): Oil yield in relation to the seed powder weight and volume of solvent

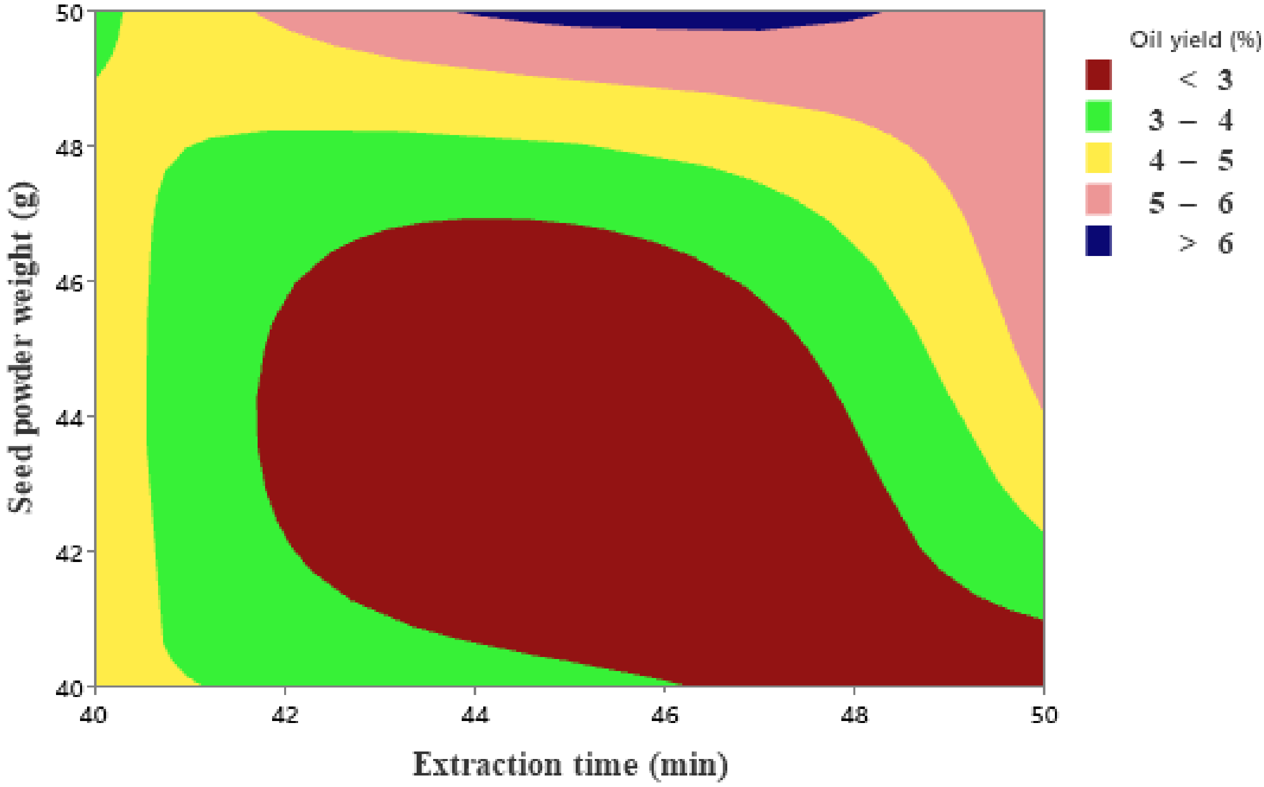

Figure 3. (c): Oil yield in relation to the seed powder weight and extraction time

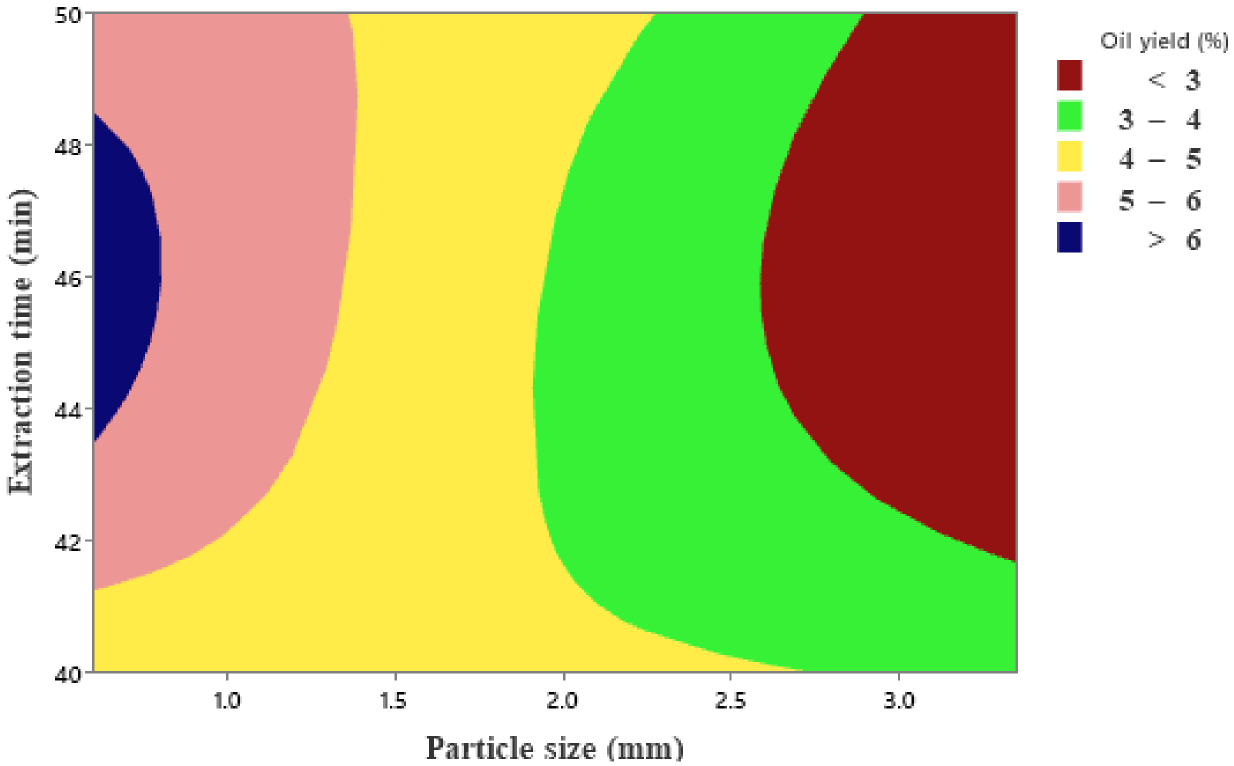

Figure 3. (d): Oil yield in relation to the particle size and extraction time

Similarly, a decrease in powder particle sizes result in higher FSO yield (Figure 3 a, d). In contrast to seed powder and particle sizes, the neither a continuous increase nor decrease in volume of solvent and extraction time factors increased the FSO yield (Figure 3 b-d) (Odetoye et al, 2016). Identifying Powder weight and particle size as critical factors directs pretreatment efforts toward milling rather than prolonged extraction. The Taguchi model supports rapid re-optimization for seed-supply variability, facilitating scale-up with minimal trial-and-error.

G. *Physicochemical Characterization of Extracted Oil*

To evaluate the quality and potential applications of the FSO recovered under optimized conditions (50 g, 0.6 mm, 250 mL, 45 min), we measured its key physicochemical properties per AOAC and ASTM methods. Results (Table 6) confirm that the oil meets standards for biodiesel feedstocks and oleochemical use.

Figure 4: Extracted FSO

Table 6: Physicochemical Properties of Optimized DSO

Property	**Measured Value**	**ASTM/AOAC Method**	**Typical Range** (Adewoye *et al.*, 2025; Adejumo *et al.*, 2019)
Color	Amber	ASTM D1500	Light amber–amber
Density @ 25 °C (g/cm³)	0.904	D4052	0.90–0.97

Refractive index @ 25 °C	1.460	D1218	1.44–1.48
Kinematic viscosity @ 40 °C (cSt)	19.8	D445	5–30
Acid value (mg KOH/g)	3.36	D664	< 5
Saponification value (mg KOH/g)	209.8	D5558	190–220
Iodine value (g I_2/100 g)	121.5	D5554	100–130
Moisture content (wt. %)	0.18	E203	< 0.2

The FSO's amber (Figure 4) hue aligns with published Flamboyant-seed oils (Adewoye *et al*., 2025; Adejumo *et al*., 2019) and indicates low pigment content. A density of 0.904 g/cm³ and refractive index of 1.460 reflect high triglyceride purity, falling within vegetable-oil norms. At 40 °C, the kinematic viscosity (19.8cSt) is suitable for biodiesel blending, balancing flow at low temperatures and pumpability. 3.36 mg KOH/g indicates minimal free-fatty-acid content, signifying oil freshness and stability against hydrolysis; it meets biodiesel feedstock criteria (< 5 mg KOH/g). 209.8 mg KOH/g suggests average molecular–weight fatty acids and confirms utility in soap and detergent formulations. 121.5 g I_2/100 g positions the oil as semidrying, suitable for surfactant production but not rapid film-forming coatings. Low moisture (< 0.2 wt. %) reduces risk of microbial growth and hydrolytic degradation during storage. Collectively, these characteristics affirm that the DSO extracted under optimized Taguchi conditions is of high purity and quality, meeting industrial specifications for biodiesel, personal-care emulsifiers, and oleochemical intermediates.

H. Comparison to Literature

Optimized yield (6.35 wt. %) is mid-range compared to 8–29 wt. % reported using exhaustive Soxhlet protocols for *Delonix regia* seeds (Adewoye *et al*., 2025; Obeta *et al*., 2025; Adejumo *et al*., 2019; Oyedeji *et al*., 2017), yet required only nine runs (Anna *et al*., 2022; Kumar *et al*., 2017). versus 20 in RSM studies (Adewoye *et al*., 2025), highlighting Taguchi's efficiency.

Table 7.: Comparative Analysis of Flamboyant Seed Oil Properties

Oil Properties	Oyedeji *et al*., (2017)	Adejumo *et al*., (2019)	Obeta *et al*., (2025)	Adewoye *et al*., 2025	This study
Colour	Amber	Amber	Light brown	Amber	Amber
Odour	Sweat-smelling	Sweet smelling	-	-	Mild aroma
Yield (%)	17.16	29.0	8.4	8.38	6.35
Moisture content (%)	10.12	-	-	-	6.13
Density (g/cm³)	0.97	0.942	0.86	0.97	0.904
Specific gravity @ 25ºC	-	-	-	-	0.904
Saponification value (mg KOH/g)	203.40	213.48	117.81	209.81	302.5
Acid value (mg KOH/g)	2.36	1.97	22.22	10.92	3.36
Free fatty acid value (mg KOH/g)	1.18	0.985	11.11	5.61	1.68
Iodine value (g iodine/100g oil)	121.03	127.92	-	23.42	121.5
Flash point (°C)	-	201.3	-	-	272.4
Pour point (°C)	-	-2	-	-	-6
Cloud point (°C)	-	-12	-	-	-2

CONCLUSION

In this work a design of experiment technique - Taguchi L9(3⁴) orthogonal array was utilized to optimize extraction process of *Delonix regia* seed oil. Nine trials screened four variables (Powder weight, particle size, solvent volume, and extraction time) revealing particle size and Powder weight were the only statistically significant factors ($p < 0.01$), while solvent volume and time had negligible impact ($p > 0.15$).

The optimal combination 50 g seed powder, 0.6mm particle size, 225 mL n-hexane, and 40 min yielded 6.35 wt. % oil, within 0.3 % of the Taguchi model's 6.35 wt. % prediction. A linear regression in coded variables explained 97 % of yield variance ($R^2 = 0.97$; adj-$R^2 = 0.94$) and guided confirmatory runs that validated model accuracy. Compared to RSM protocols requiring 20–30 runs for four-factor optimization, the Taguchi L9 design delivered equivalent yield improvements in only nine experiments, demonstrating marked efficiency gains. These findings provide a robust, resource-efficient blueprint for maximizing oil recovery from *Delonix regia* seeds, leveraging a small experiment set to achieve high yields.

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