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Process Optimization for *Madhuca indica* Seed Kernel Oil Extraction and Evaluation of its Potential for Biodiesel Production

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ABSTRACT

The current research aims to optimize the solvent-based oil extraction process from Mahua (*Madhuca indica*) seed using response surface methodology and biodiesel production using heterogeneous catalysts. The oil extraction was varied through the levels of process parameters including extraction temperature (60 to 80°C), solvent-to-seed ratio (3 to 9 wt/wt), and time (2 to 4 h). The experiments were designed following the Central Composite model. The regression model provided optimal values for the selected process parameters based on the extraction yield percentage. To ensure the model's reliability, it was experimentally validated. Maximum experimental oil yields of 50.9% were obtained at an optimized extraction scenario of 70 °C extraction temperature, solvent-to-seed ratio of 6 wt/wt, and time 4 h. The extracted oil's physicochemical properties and fatty acid composition were tested. Also, using copper-coated dolomite as a catalyst, the extracted oil was transformed into biodiesel via transesterification. The FAME (94.31%) content of the prepared biodiesel was determined via gas chromatography. As a result, the findings of this study will be useful in further research into the use of *Madhuca indica* as a potential feedstock for biodiesel production.

INTRODUCTION

Fast economic growth around the world has caused an increase in unusual energy demand. The majority of energy requirements are met by fossil fuels such as petroleum and coal (Hong et al. 2023). As a result, the fuel reserves are gradually depleted. Beyond that, greenhouse emissions from fossil fuels harm global weather. In addition, the use of fossil fuels contributed to up to 62% of the worldwide emissions of greenhouse gases (Mathiarasi & Partha 2016, Cako et al. 2022, Mukhtar et al. 2022). Likewise, the transport industry alone accounted for approximately 16% of total emissions. As a result, there is a quick need to look into sustainable and alternate forms of energy for worldwide use while attempting to reduce the environmental impact of growth (Borges & Díaz 2012, Keneni & Marchetti 2017, Krishnamoorthy et al. 2023).

A circular bioeconomy concept for biomass entails the sustainable, effective use of biological resources in a way that decreases waste and improves value for the resources' entire lifecycle. This strategy is consistent with the principles of the circular economy, which seeks to reduce, reuse, recycle, and regenerate resources to develop a more resilient and environmentally friendly economy. Furthermore, future strategies for decarbonization are required to grow and establish renewables to reduce dependence on fossil fuels and safeguard the environment from climate change and air pollution (Jan et al. 2023). As an alternative to diesel, biodiesel is considered a promising option that can be used to address both the challenges of fossil fuel depletion and greenhouse gas emissions at the same time. Biodiesel's global popularity has grown in the past decade (Baskar et al. 2018, Milano et al. 2022, Mulyatun et al. 2022).

Biodiesel research has progressed, with an increasing focus on sustainability, lowering transportation fuel's carbon footprint, and energy security. Furthermore, technological advancements and greater awareness of feedstock options could have opened up new avenues for biodiesel production. Government policies promoting renewable fuels influenced both national and international research efforts. Researchers were investigating the efficacy of these policies as well as their effects on the biodiesel industry (Osman et al. 2021, Al-Muhtaseb et al. 2022). Biodiesel is made from renewable sources such as plant and animal waste, and a few plants, such as Jatropha and Calophyllum, are specifically grown to produce biodiesel. *Madhuca indica* belongs to the Sapotaceae family, commonly known as Mahua or Indian Butter Tree, and has been considered a potential biofuel feedstock due to its oil-rich seeds and sustainability. *Madhuca indica* is found primarily in India's tropical and subtropical regions, as well as in parts of Southeast Asia. It grows in deciduous forests, tropical and subtropical regions, and is adaptable to a wide range of soil types. However, its successful use as a biofuel source would require addressing challenges related to yield variability, processing, infrastructure, and environmental impact (Tirkey et al. 2022).

As a result, biodiesel is viewed as an environmentally friendly, renewable source of energy that is less hazardous to the ecosystem than conventional energy derived from petroleum or diesel (Sá et al. 2021). Bio-oil can be extracted from biomasses in several ways, including solvent extraction, mechanical press, and enzymatic. While the extraction technique used by Soxhlet has several benefits, it also comes with some drawbacks (Salehzadeh et al. 2014, Jayakumar et al. 2021, Aparamarta et al. 2022). Long extraction times, the need for large solvent volumes, and the risk of thermal degradation for thermally sensitive compounds are among them. As a result, for effective bio-oil extraction, it is critical to consider these factors and optimize the extraction conditions in accordance. Abdi Sharma et al. examined the ultrasound amplitude level (20-40%), extraction time (30-60 min), and solvent-to-seed ratio (10-20 mL g^{-1}) were the process parameters considered. The regression model provided optimal values for these process parameters, along with the related extraction yield (Thanikodi et al. 2023).

Following our comprehensive literature review, no optimization study regarding the extraction of oil from *Madhuca indica* has been reported. The findings contribute to filling a significant gap in the literature by providing a detailed and optimized approach to oil extraction from mahua seeds, followed by its conversion into biodiesel. Using RSM along with the central composite experimental designs, an optimized condition for solvent-based oil extraction from *Madhuca indica* was obtained. The objective of this research is to determine the effect of process parameters, including extraction time, temperature, and solvent-to-seed ratio, on the bio-oil yield from Maduca indica seed. The obtained optimum process parameter levels from the regression model were validated through experimental results. The extracted oil was then characterized before being transformed into biodiesel via transesterification. Followed by the prepared biodiesel, also characterized by ASTM D6751 regulations.

MATERIALS AND METHODS

Oil Extraction

Soxhlet extraction was used for the extraction of mahua seed kernel oil. When compared to other procedures, the constant cycling of solvent through the sample facilitates an effective extraction of the oil and produces larger yields. Choosing the right solvent based on the type of substance to be extracted can be flexible when using Soxhlet extraction. Depending on the polarity and other characteristics of the oil, several solvents can be utilized. The seeds are collected from the ripe stage fruits fallen from the mahua tree, and the seeds were spread out to dry in an area with adequate ventilation. The drying process removes moisture in the seeds and sets them up for extraction.

After drying, the seeds' outer husk was removed, and afterwards the seeds were finely powdered. The ground seed powder is then used for oil extraction. The Soxhlet extraction method was followed for oil extraction using hexane as solvent. The thimble is filled with biomass, and the hot solvent extracts the desired compound from the powdered seeds. The chemical reaction continues to cycle with the system after extracting the compound from the sample. The desired compound gradually collects through the continuous boil and condensation of solvents. This process is repeated several times to ensure complete extraction.

The levels of influencing process parameters for the oil extraction process, including temperature (60 to 80°C), time (2 to 4 h), and solvent-to-oil ratio (3 to 9 wt/wt) were followed from previous studies (Rodríguez-Solana et al. 2014, Mujeeb et al. 2021, Mehdi et al. 2023). The experimental model with a total of twenty experiments was developed using RSM with the central composite approach. The obtained yield value from each test was entered into the model developed by the Design Expert to forecast the optimum values of each process parameter. A maximum of 50.9 % oil was extracted for the conditions of temperature (70 °C), time (4 h), and solvent-to-oil ratio (6 wt/wt). To remove any impurities or solid particles, the extracted oil is filtered. Fig. 1 shows the seeds are extracted by removing the skin and husk from the seed shell used for bio-oil extraction, kernel powder, and deoiled cake.

Transesterification

The reaction rate and biodiesel yields are influenced by several factors, including the reaction duration, reaction temperature, methanol-to-oil molar ratio, and the weight percentage of the catalyst (Rocha-Meneses et al. 2023). Nanoparticle-doped catalysts have the potential to improve the efficiency and sustainability of biodiesel production.

Fig. 1: *Madhuca indica* Linn (a) Tree (b) (i) seed (ii) seed husk (iii) kernel (c) *Madhuca indica* oil (d) *Madhuca indica* deoiled cake.

They provide benefits such as increased catalytic activity, decreased waste, and potentially higher-quality biodiesel (Gurunathan & Ravi 2015).

The Teflon-coated reactor with a temperature-controlled magnetic stirrer was used for the biodiesel preparation from *Madhuca indica* oil. The condenser is positioned over the reactor to prevent methanol leakage through boiling. The suggested optimal reaction was run for 6 h at 75°C with a methanol to oil molar ratio of 20:1 and copper-coated dolomite catalyst of 5 wt.%. For the synthesis of biodiesel, copper-coated dolomite is preferred due to its catalytic activity, stability, reusability, and potential for enhanced transesterification process efficiency. This catalyst is a viable way to improve the biodiesel production processes' cost-effectiveness and sustainability.

Following the end of the reaction time, due to the difference in density, the reactants were allowed to settle with the layers of biodiesel, glycerol, and catalyst at the bottom. The glycerol was removed by gravity separation, followed by the catalyst being recovered from the mixture through a centrifuge process for the next reaction. In the end, to obtain pure biodiesel, the contaminants are removed by water wash and the suspended water particles are heated to evaporate. Fig. 2 represents the full process layout for oil extraction and biodiesel production.

Response Surface Methodology

RSM is a statistical technique that helps in the understanding of the relationship between input variables and the output response of the model. Design Expert Version 12.0 was employed to model the extraction's process parameters and optimize the operating conditions. The experimental model was designed through central composite design (CCD) because it offers an abundance of details with a minimum experiment. CCD is used to generate a sequence of experimental runs, each with its own set of factor levels, including the central point, factorial points, and axial points. Experiments are carried out using the CCD matrix, and the results are recorded. Regression analysis is used to fit a second-order polynomial model to the experimental data. The response surface is represented by this model. The response surface model is examined to determine factor effects, interactions, and surface curvature. Numerical optimization techniques can be used to find the optimal factor settings that maximize the output response. Once the optimal conditions have been determined, additional experiments may be carried out to confirm the predicted results. In this experimental work, A: temperature (h), B: solvent-to-seed ratio (wt/wt), and C: time (h) are the three selected independent variables based on previous literature. The table shows how each parameter in the experiment was coded to levels -1, 0, and +1. The optimized process parameter levels were identified through a regression model.

FAME Analysis

The fatty acid composition of the extracted *Madhuca indica* oil was determined using gas chromatography (Shimadzu, SH-Rxi-5Sil Ms). It was further employed to determine the linolenic methyl ester percentage and fatty acid methyl ester (FAME) content of the produced biodiesel following the EN 14103:2011 standard.

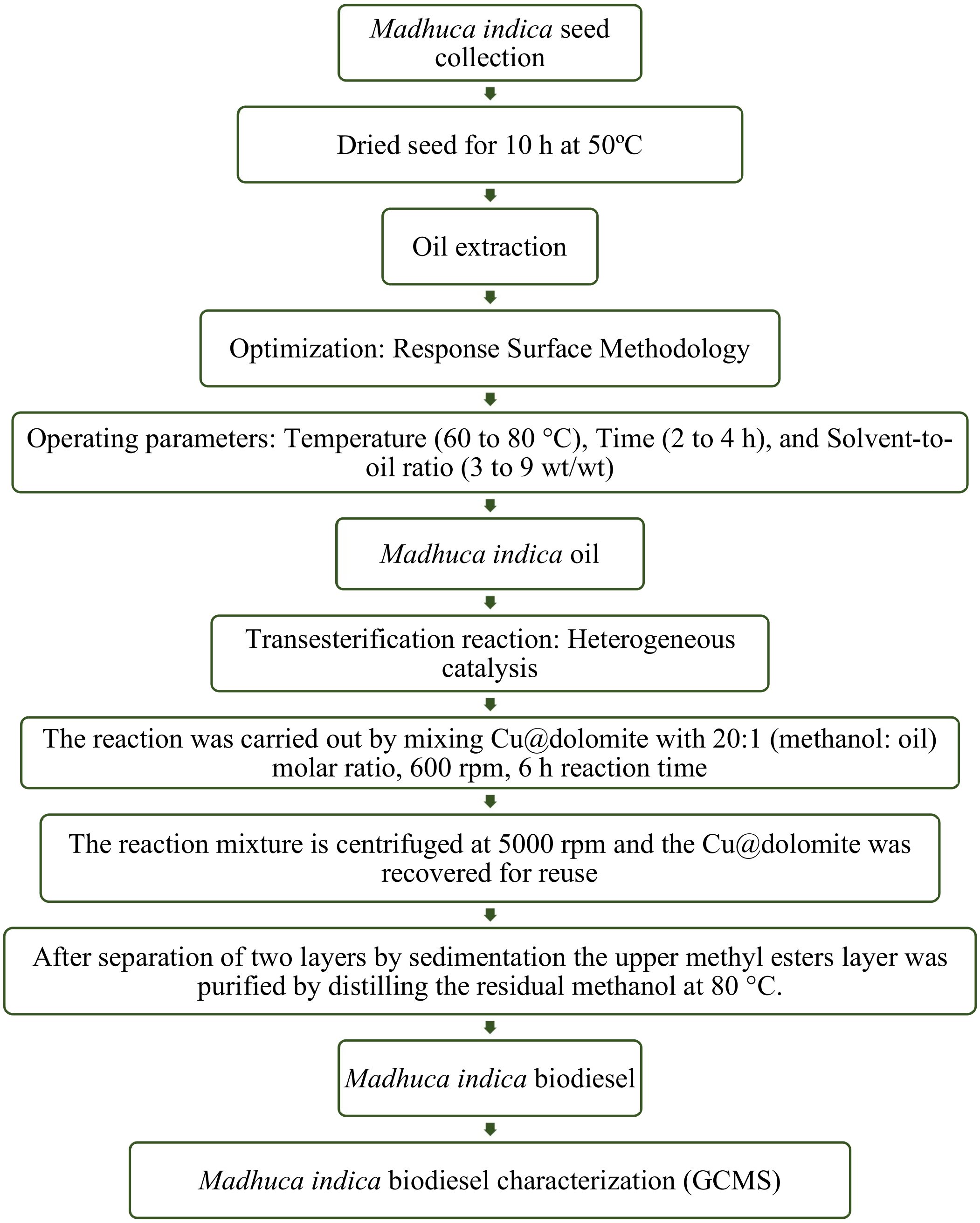

Fig. 2: Process layout for *Madhuca indica* oil extraction and biodiesel production.

RESULTS AND DISCUSSION

Response Surface Methodology for Oil Extraction

The Central Composite experimental model was used in the optimization work to investigate the effect of different variables, including temperature, time, and solvent-to-seed ratio, on *Madhuca indica* oil extraction yield. By applying the previously mentioned coded levels, the central composite experimental model developed a total of 20 experiments shown in Table 1. The obtained yield value from each test was entered into the model developed by the Design Expert to forecast the optimum values of each process parameter. The *Maduca indica* oil yield was predicted by the second-order regression model equation (2). The regression

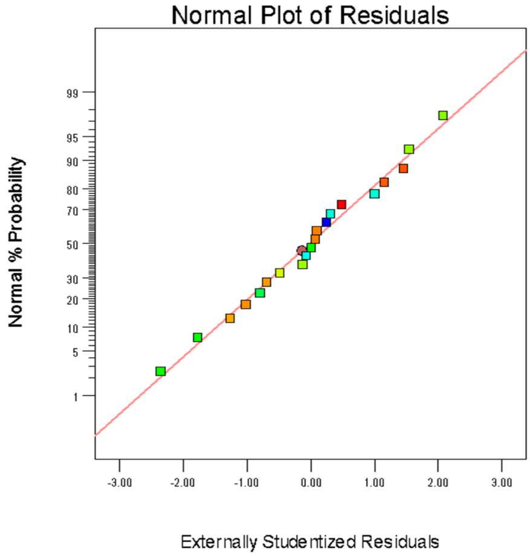

Fig. 3: Statistical analysis of the response surface quadratic model for a plot of normal % probability to externally studentized residual.

Table 1: Central composite design matrix and the responses of the dependent variable-biodiesel yield from *Madhuca indica* oil.

StdOrder	RunOrder	PtType	Blocks	T	S_R	Time	Yield (wt%)	
							Experimental	Predicted
1	1	1	1	60	3	2	12.6	12.4
2	2	1	1	80	3	2	29.2	29.7
3	3	1	1	60	9	2	23.7	23.5
4	4	1	1	80	9	2	36.7	35.6
5	5	1	1	60	3	4	32.1	33
6	6	1	1	80	3	4	37.7	37.8
7	7	1	1	60	9	4	23.9	23.3
8	8	1	1	80	9	4	22.9	22.9
9	9	-1	1	60	6	3	31.8	31.8
10	10	-1	1	80	6	3	39.8	40.2
11	11	-1	1	70	3	3	37.3	35.9
12	12	-1	1	70	9	3	32.3	34.1
13	13	-1	1	70	6	2	45.5	46.5
14	14	-1	1	70	6	4	50.9	50.4
15	15	0	1	70	6	3	46.2	46.1
16	16	0	1	70	6	3	47.5	46.1
17	17	0	1	70	6	3	44.6	46.1
18	18	0	1	70	6	3	46.2	46.1
19	19	0	1	70	6	3	47.8	46.1
20	20	0	1	70	6	3	45.2	46.1

T (°C) - Extraction temperature; S_R- solvent to seed ratio (wt/wt); θ (h)- Extraction time.

model provides optimal values for independent variables and their impact on the output by iteratively adjusting the model's coefficients during the training process to minimize the error between predicted and actual values. The final coefficients represent the model's estimate of the relationship between each independent variable and the output variable. The significance of regression model coefficients was analyzed using ANOVA, which is shown in Table 2.

According to the ANOVA results, the model's p-value is very low (less than 0.005), implying that the developed model is significant in predicting *Madhuca indica* oil yield (Kodgire et al. 2023). In addition, the p-value for the lack of fit is 0.419, which is regarded as insignificant. To determine how well the model fits the data, its coefficients and goodness-of-fit statistics were examined. In this way, it demonstrates that the developed regression model fits the experimental results well. The obtained R^2 (0.9918) value depicts that the regression model describes over 99.18% of the variability in *Madhuca indica* oil extraction (Liu et al. 2023). The significant R^2 value additionally suggests that data points were very close to the regression line, indicating that the experimental and predicted results agreed well, as shown in Fig. 3. The predicted values for the optimal conditions of temperature, time, and solvent-to-seed ratio were noted as 50.4%.

Meanwhile, to validate the model, the experiment was conducted at the optimum data points, and the experimental yield was obtained as 50.9%. Nonetheless, the variation between the two values is relatively low (0.5%), demonstrating that the regression model is good at predicting *Madhuca indica* seed extraction yield (Sundaramahalingam et al. 2021, Dharmalingam et al. 2023).

$$\% \, oil \, extraction = 15.74\,T + 22.68\,S_R + 20.18\,\theta - 0.10\,T^2 - 1.23\,S_R^2 + 2.36\,\theta^2 - 0.043\,T \times S_R - 0.31\,T \times \theta - 1.734\,S_R \times \theta - 619.8$$

Fig. 4 shows, Three-dimensional plots to examine the effect of process parameters (extraction temperature, extraction time, and solvent-to-seed ratio) in the *Madhuca indica* oil extraction yield. Overall, it has been discovered that a specific range of values for each variable leads to a rise in oil yield. When the parametric values crossed the specified range, the extraction yield decreased, resulting in non-optimal operating conditions.

Fig. (4. a) shows the combined effect between solvent-to-seed ratio and temperature on oil yield. The convex pattern shows that the central points play the dominant role. Oil yield improves significantly as seed to seed-to-solvent ratio and extraction temperature increase until the central data point is reached. After this point, the oil yield begins to fall. When the seed-to-solvent ratio is from 3 to 6 wt/wt, the extracted oil yield increases, whereas a similar case is observed when the extraction temperature is varied from 60 to 70°C.

Table 2: Analysis of Variance for biodiesel yield from *Madhuca indica* oil.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	2058.25	228.694	133.72	0.000
Linear	3	226.21	75.404	44.09	0.000
T	1	178.51	178.506	104.37	0.000
S_R	1	8.78	8.780	5.13	0.047
θ	1	38.93	38.927	22.76	0.001
Square	3	1523.85	507.949	296.99	0.000
T*T	1	279.69	279.695	163.54	0.000
S_R * S_R	1	338.52	338.522	197.93	0.000
θ * θ	1	15.25	15.252	8.92	0.014
2-Way Interaction	3	308.19	102.729	60.06	0.000
T* S_R	1	13.16	13.158	7.69	0.020
T* θ	1	78.50	78.500	45.90	0.000
S_R* θ	1	216.53	216.528	126.60	0.000
Error	10	17.10	1.710		
Lack-of-Fit	5	9.37	1.875	1.21	0.419
Pure Error	5	7.73	1.546		
Total	19	2075.35			
R^2 = 98.18%; R^2 (pred) = 95.23%; R^2 (adj) = 98.43%					

T (°C) - Reaction temperature; S_R- solvent to seed ratio (wt/wt); θ (h)- Reaction time.

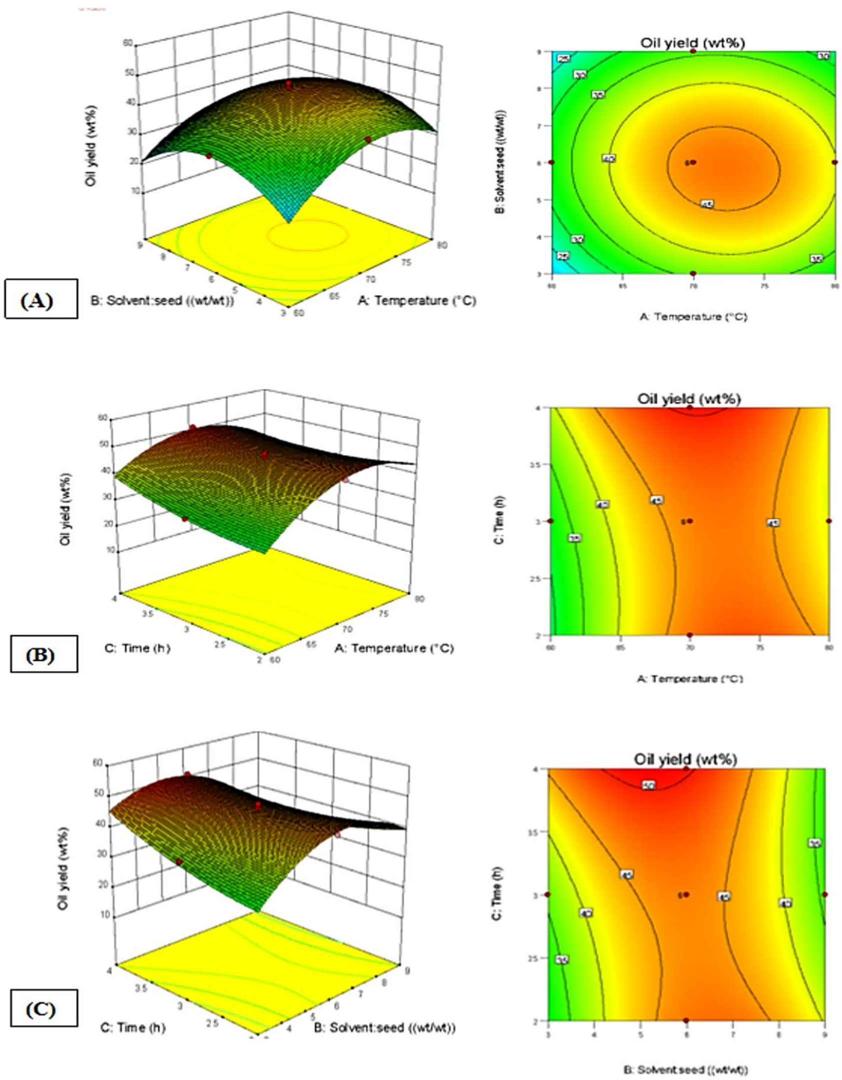

Fig. 4: Response surface graph showing interaction effects between solvent: seed ratio and temperature (A), temperature and time (B), and solvent: seed ratio and time (C).

Fig. (4. b) shows oil yield rises as extraction time increases. The reaction goes for a longer period as time increases. As a result of this phenomenon, more amount of heat is produced (Prabakaran et al. 2021, Sebayang et al. 2023). This could lead to the breaking down of the cell wall, allowing the solvent molecule to penetrate the cell. Fig. (4. c) demonstrates a 3D plot of the interaction between solvent-to-seed ratio and extraction time. The catalyst weight (%) increased to 6wt%, which marked a considerable rise in the percentage output of biodiesel. Still, because of the high rate of mass transfer resistance in the transesterification process using the excess catalyst, increasing the catalyst content further reduces the output of biodiesel. While the solvent-to-seed ratio ranges from 3 to 6 % wt/wt, the oil yield increases, resulting in a maximum yield of 50.9%.

Quality Analysis of Biodiesel

Individual FAMEs in a biodiesel sample can be separated and identified using GC-MS. Table 3 illustrates the FAME amount in *Madhuca indica* biodiesel as estimated by gas chromatography. Fig. 5 represents the overall GC-MS result of *Madhuca indica* biodiesel. EN 14103:2011 suggests a minimal FAME level of 90 %wt/wt, with linolenic acid methyl ester (C18:3) linolenic ranging between 1 and 15 (wt/wt). The FAME percentage of *Madhuca* biodiesel is 94.31 %wt/wt, which is significantly higher than the EN 14103:2011 recommended value.

Table 3: GC-MS result of *Madhuca indica* biodiesel.

Peak#	Retention time	Area %	Name
1	3.083	0.77	2-Butene, 1-chloro-2-methyl-
2	6.638	0.32	3-Hydroxy-3-methyl-2-butanone
3	6.863	0.63	Nonane, 5-(2-methyl propyl)-
4	7.644	0.16	1,1-Dimethyl-3-chloropropanol
8	10.67	0.28	Heptadecane, 2,6,10,15-tetramethyl-
9	10.126	0.61	Pentadecane
11	11.134	0.47	Eicosane
17	13.535	0.34	Tetradecanoic acid, 12-methyl-, methyl ester
18	13.663	0.49	Nonadecane
27	16.997	0.78	Pentadecanoic acid, 14-methyl-, methyl ester
28	17.633	0.27	2-Methyltriacontane
29	21.483	1.02	Methyl tetradecanoate
30	23.043	0.14	2-Butenedioic acid (Z)-, dibutyl ester
31	25.33	31.81	Hexadecanoic acid, methyl ester
33	26.82	0.39	Phenol, 3,5-bis(1,1-dimethyl ethyl)-
34	27.671	0.28	Benzoic acid, 2-methyl-, (2-isopropyl-5-methyl
35	29.157	20.04	Methyl stearate
36	36 29.600	30.96	9-Octadecenoic acid (Z)-, methyl ester
37	37 30.759	10.24	9,12-Octadecadienoic acid (Z, Z)-, methyl ester

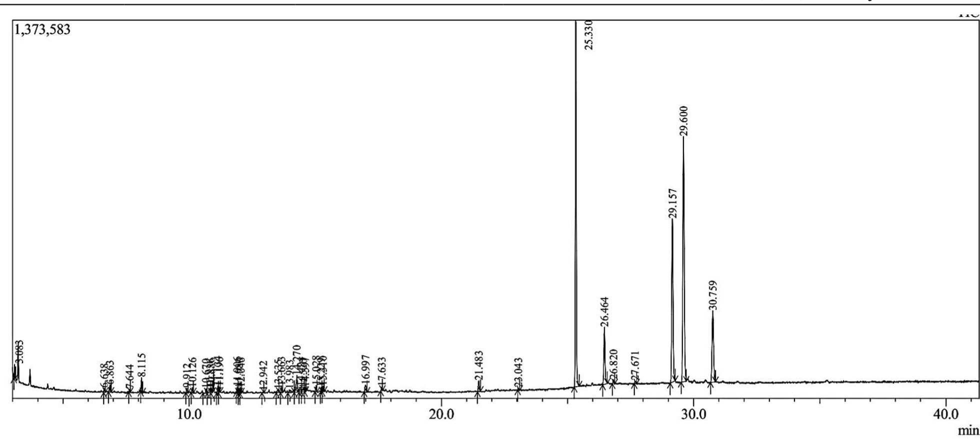

Fig. 5: Overall GC-MS result of *Madhuca indica* biodiesel.

The physicochemical properties of *Madhuca indica* bio-oil and biodiesel are shown in Table 4. The density of biodiesel may be measured at a temperature of 15°C, which makes it possible to characterize its mass per unit volume in relation to storage and transit conditions. Density at room temperature is frequently used to evaluate the quality and suitability of biodiesel to requirements. As this temperature is more indicative of the conditions under which biodiesel is typically utilized, particularly in diesel engines, the kinematic viscosity of biodiesel is evaluated at 40°C. Diesel engines run at high temperatures; thus, biodiesel is usually mixed with diesel to be used as fuel. It is possible to evaluate how well the biodiesel flows and lubricates under operating circumstances by measuring the kinematic viscosity at 40°C.

Table 4: Physicochemical properties of *Madhuca indica* bio-oil and biodiesel.

Properties	Diesel	*Madhuca indica* bio-oil	*Madhuca indica* Biodiesel
Density @ 15°C [$g.cc^{-1}$]	0.834	0.960	0.870
Kinematic viscosity @ 40°C [cSt]	2.5	24.7	5.2
Calorific value [$MJ.kg^{-1}$]	43.5	36.5	35.0
Cetane number	45	46	52
Flashpoint [°C]	51	232	148
Pour point [°C]	-21.2	8	2.67
Iodine Number [$gI_2.100g^{-1}$]	38.3	88	70
Water Content [%]	-	0.02	-

Table 5: A comparison of current investigations with earlier studies

Biomass	Operating Conditions	Yield	Reference
Madhuca indica	Soxhlet technique: Temperature - 70°C; reaction time 4 h and Solvent-to-seed ratio of 6 wt/wt, Solvent – n-hexane; Transesterification: Reaction time 6 h at 75 °C with a methanol to oil molar ratio of 20:1 and copper-coated dolomite catalyst 5 wt.%	Bio-oil Yield 50.9% Biodiesel Yield 94.31%	Present
Madhuca indica	Ultrasonication technique: temperature 50 °C, Contact time 20 min, seed to solvent ratio (diethyl ether:ethanol) 1:10 (3:1)	Bio-oil Yield 82%	(Baskar et al. 2018)
Stoechospermum marginatum	Soxhlet technique; Temperature - 45°C; reaction period – 72 h; Solvent – n-hexane;	Bio-oil Yield 24.4%	(Venkatesan et al. 2017)
Sargassum wightii	Soxhlet technique; reaction period – 12 h; solvent-to-solid ratio – 6:1	Bio-oil yield – 25%	(Kumar et al. 2015)
Azolla microphylla	Soxhlet technique; Solvent - chloroform and methanol (2:1); Reaction temperature 65°C; Reaction time 12 h	Bio-oil yield – 17%	(Thiruvenkatachari et al. 2021)
Cladophora sp.	Soxhlet technique; Reaction time 18 h; Solvent – Trichloethylene [1:10 $g.mL^{-1}$]	Bio-oil yield – 31.1%	(Firemichael et al. 2020)
Madhuca indica	Transesterification: Reaction temperature 60 °C; Methanol-to-oil ratio (6:1 molar ratio) and 0.7% w/v KOH as an alkaline catalyst to produce biodiesel	Biodiesel yield – 98%	(Ghadge & Raheman 2006)
Ulva lactuca	Transesterification: Oil to methanol molar ratio 1:12; Catalyst loading 1.5 wt%; Reaction temperature 63°C; Reaction time 1.7 h	Biodiesel yield – 88.77%	(Binhweel et al. 2023)
Azolla pinnata	Transesterification: Methanol to oil molar ratio 30:1; heterogeneous catalyst weight 4%; operation temperature 70°C	Biodiesel yield – 88.7%	(Prabakaran et al. 2021)
Waste and crude vegetable oils	Heterogonous acid Catalysts (Activated Carbon supported-SO_3H, SBA-15, HPA); Solvent – Methanol.	Biodiesel yield – 90%	(Hara 2010)
Canola oil, rapeseed oil, waste cooking oil	Hydroxyapatite catalyst from waste quail beaks (7 wt %); reaction time (4 h); oil to methanol molar ratio (1:12);	Biodiesel yield – 89.4, 96.7 and 91.7%	(Khan et al. 2020)
Triacetin	Base supported carbon catalysts CaO supported on nanoporous carbon (NC-2); reaction time (4 h); oil to methanol molar ratio (1:6); Temperature 60°C.	Biodiesel yield – 99%	(Zu et al. 2010)

The methodology, process parameters, and output responses of the present experimental study for both bio-oil extraction and biodiesel production were compared with the previous studies in Table 5. When evaluating the potential of mahua oil for biodiesel production, a number of critical metrics, including fatty acid composition, viscosity, and cold flow qualities, can be used to compare the quality of the oil to other feedstocks. Every feedstock has a distinct composition and set of characteristics that affect the final biodiesel's applicability and quality.

CONCLUSION

In summary, *Madhuca indica* has the potential to be a valuable biofuel feedstock due to its high oil content and sustainability. The present research aimed to optimize oil extraction from *Madhuca indica* seed via RSM with a central composite experimental design. The optimal values for the independent variables analyzed for the solvent extraction were 70 °C, 6 %wt/wt, and 4 h for extraction temperature, solvent-to-seed ratio, and time, respectively. Under this optimized scenario, the forecasted and experimental oil yields were 50.4% and 50.9%, respectively, which demonstrates the regression model's reliability. The physicochemical properties were measured as per ASTM D6751 regulations. The biodiesel was produced from the extracted oil with a 94.31% yield through transesterification. The measured physicochemical properties of biodiesel were within the specified ranges of ASTM D6751. As a result, *Madhuca indica* seeds can be considered a viable feedstock for the production of biodiesel. Future research direction for this experimental work is to improve extraction efficiency and consider using innovative technologies such as ultrasound-assisted extraction or microwave-assisted extraction. Furthermore, a life cycle analysis (LCA) has to be conducted to assess the environmental sustainability of *Madhuca indica* seed kernel oil-derived biodiesel production and use.

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