

## Optimizing Aluminium 6061 Turning using Kesambi Oil-Based Cutting Fluid and Response Surface Methodology to Reduce Surface Roughness

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### ABSTRACT

This study investigates the viability of Kesambi oil (*Schleichera oleosa*) as an environmentally sustainable, bio-based cutting fluid to reduce surface roughness during the turning of Aluminium 6061. The study employs Response Surface Methodology in conjunction with a Central Composite Design to identify the optimal parameter combination between two primary variables, including the composition of Kesambi oil and the depth of cut during machining. The best configuration, comprising 19.57% Kesambi oil and a cutting depth of 0.99 mm, yielded a surface roughness of 3.61  $\mu\text{m}$ , closely matching the predicted value of 3.59  $\mu\text{m}$ . A Fourier Transform Infrared Spectroscopy was conducted to indicate the presence of a thin lubricating film on the surface. This film can reduce the friction and enhance the high surface quality. Generally, the results show that Kesambi oil is effective and sustainable compared to conventional petroleum-based cutting fluids.

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**Keywords:** Aluminium 6061, bio-based cutting fluid, Kesambi oil, response surface methodology, surface roughness.

## I. Introduction

Machining is the process to transform raw materials into functional products by the help of a cutting tool to remove material to get a product with the desired shape and dimensions [1]. The common material used in the manufacturing process is Aluminium 6061 (Al-6061) because of its properties such as lightweight, high strength-to-weight ratio, corrosion resistance, and excellent thermal stability. Despite its advantages, machining Al-6061 has significant challenges, such as rapid tool wear, increased surface roughness, and heat generated during machining that affect quality and dimension accuracy of final product [2].

During the machining process, heat that accumulates in the cutting zone is able to reduce the material's performance and increase tool wear, causing lower efficiency and raising production costs, so cutting fluids are applied as a cooling fluid. These fluids improve the lubrication, minimizing friction, dissipating heat, and flushing away chips from the cutting zone [3]. Petroleum-based cutting fluids are conventional cutting fluids that have been known to be effective in improving tool life and surface finish. However, they are non-biodegradable, toxic, and contribute to environmental pollution during use and disposal [4], so they need an alternative cutting fluid that is environmentally friendly and sustainable with comparable or even better performance than conventional cutting fluids [5].

Many researchers have reported the potential of bio-based cutting fluids derived from renewable vegetable oils, such as canola, soybean, palm, and coconut oil. These oils are non-



toxic and biodegradable, and they have good physicochemical properties, such as a high viscosity index, good lubrication, and high flash point [6]. However, since these oils are edible and linked to food security concerns, their widespread industrial use is less desirable. Their stability during high-temperature activities is limited by their capacity for oxidative decomposition under continuous heat exposure [7]. Therefore, Kesambi oil (*Schleichera oleosa*) offers a good alternative. Kesambi oil is a non-edible vegetable oil produced from a plant species native to South and Southeast Asia, particularly Java [8]. They have been utilized in the production of biodiesel due to its superior lubricating qualities, high viscosity, high flash point, and good oxidative stability [9]. Kesambi oil also contains a high proportion of long-chain fatty acids and natural antioxidants, which increase its resistance to thermal breakdown during machining [10], improve corrosion resistance, reduce friction and tool wear compared to coconut or soybean oil [11]. Basuki *et al.* [12] reported that Kesambi oil can improve surface quality, reduce energy consumption, and reduce overall machining costs through drop lubrication. The potential of Kesambi oil as a cutting fluid, especially in precision machining of Al-6061, needs to be developed so that it can be used effectively as a cutting fluid. Moreover, the technique of drop lubrication, facilitated by advanced response surface methodology (RSM), can optimize this oil for various applications [13].

This study aims to evaluate the potential of Kesambi oil as bio-based cutting fluid for improving surface quality in the turning of Aluminium 6061. This study focuses on assessing the ability of Kesambi oil to reduce surface roughness. The study employs RSM to systematically optimize the effectiveness of cutting parameters. Additionally, the comparison between Kesambi oil and petroleum-based oil performance as cutting fluids is conducted to support the transformation to more sustainable and resource-efficient manufacturing process.

## II. Material and Methods

### 1. Materials

The material of Al-6061 was used as the workpiece material. A carbide tool was used for the turning process due to its durability and effectiveness in machining operations. The compositions of Kesambi oil cutting fluids include Kesambi oil itself (Indonesia), surfactant (Polysorbate 80), and distilled water.

### 2. Sample Preparation

Kesambi oil as a cutting fluid was obtained by the emulsification process of Kesambi oil, Polysorbate 80 as surfactant, and distilled water. The ingredients Kesambi oil then mixed using standard laboratory magnetic stirrer (760 rpm, 15 min.), in a 500 ml sample bottle, to achieve homogeneity. The result of Kesambi oil as a cutting fluid was then utilized in the machining process. The Al-6061 workpieces were prepared by conducting a simple surface cleaning using a clean cloth to remove visible dust, oil, or debris. A visual inspection was then performed to ensure the material surface was free from noticeable surface defects or damage. This preparation was done to ensure that all samples were in a comparable and acceptable condition for the machining process.

### 3. Experimental Set-up

The cutting process was conducted using a lathe machine (Krisbow lathe type KW15-486, Indonesia). Feed rate of 0.205 mm/rev, spindle speed of 700 rpm, and a cutting depth as per the design of experiments highlighted in Table 1 were applied as cutting parameters. The application of cutting fluid was done by using a drop lubrication system at

the rate of 300 ml/h through a nozzle positioned at the tool-workpiece interface, with the fluid reservoir positioned one meter above the lathe machine.

#### 4. Response Surface Methodology Parameters

The parameters, including cutting speed, depth of cut, feed rate, and the composition of the Kesambi oil-based bio-cutting fluid, are considered. The parameters were systematically varied to investigate their impact on the surface roughness of the studied materials. Central Composite Design (CCD) was conducted under the framework of RSM by incorporating two factors of depth of cut and the composition of the bio-cutting fluid. A complete 14-series of experiments was conducted with the center points replicated to ensure accuracy.

The specific values for each parameter are cutting speed of 700 rpm; feed rate of 0.205 mm/rev; depth of cut ( $X_2$ ): varied between 0.3 mm and 1.7 mm, as defined by the CCD levels; Kesambi oil composition ( $X_1$ ): varied between 5.9% and 34.1%, as defined by the CCD levels. The details of the CCD design and corresponding experimental runs are shown in Table 1. This design included 14 samples in total, with 4 axial points, 4 factorial points, and 6 center points.

#### 5. Statistical Analysis

Data were statistically analyzed using MINITAB 21 software to develop predictive models using a regression model and analysis of variance (ANOVA) to determine the significant difference among the independent variables. The model was validated to find the optimal combination of machining parameters and fluid composition to minimize surface roughness.

#### 6. Characterization

Surface roughness ( $R_a$ ) was recorded using a portable contact profilometer (stylus-type surface roughness tester). The Al-6061 samples were placed on a flat surface, and dial indicator of the profilometer was positioned on the measured surface, then, the measurement was started. The length and shape of the chips generated by turning process were measured using a caliper. Roughness data was analyzed using MINITAB 21 as the response variable.

Chips from the turning process of Al-6061 were collected and subjected to Fourier-transform infrared spectroscopy (FTIR) with attenuated total reflectance (ATR). The chips were positioned on the spectrophotometer's diamond surface, and the device was then used to record the spectrum. In order to shed light on any chemical changes taking place throughout the machining process, the functional groups present were identified by analyzing the data that was collected.

### III. Results and Discussions

#### 1. Surface Roughness Analysis

The surface roughness is summarized in Table 1. This study examined the influence of varying compositions of Kesambi oil-based bio-cutting fluid and different depths of cut on the surface roughness value ( $R_a$ ) of Al-6061 during the turning process. The surface roughness values ranged from 3.303  $\mu\text{m}$  to 4.660  $\mu\text{m}$ . Although relatively high for finishing operations, the surface value range is reasonably considered in the context of roughing operations, which were the focus of this study.

**Table 1.** Surface roughness results

Factor		Surface Roughness Ra ( $\mu\text{m}$ )
Composition ( $X_1$ )	Depth of Cut ( $X_2$ )	
10	0.5	4.264
30	0.5	4.516
10	1.5	4.498
30	1.5	4.660
20	1	3.745
20	1	3.569
20	1	3.696
5.9	1	4.425
34.1	1	4.454
20	0.3	3.704
20	1.7	3.454
20	1	3.303
20	1	3.545
20	1	3.729

The primary objective of this experiment was to investigate the general behavior and effectiveness of the bio-cutting fluid under moderate-to-heavy cutting loads, rather than to achieve ultra-fine surface finishes. The high depth of cut cutting parameters were selected to reflect roughing conditions, where material removal rate is prioritized over surface quality.

The lowest surface roughness (3.303  $\mu\text{m}$ ) was obtained at a composition of 20% Kesambi oil and a depth of cut of 1.0 mm. This combination likely provided an optimal balance of lubrication and cooling, effectively reducing friction and cutting temperature, which contributed to a smoother surface compared to other conditions. While the overall Ra values may not qualify for fine finishing, the trends observed remain valuable for evaluating the tribological performance of the cutting fluid during preliminary or bulk machining stages.

## 2. Response Surface Methodology and Model Optimization

The surface roughness data were processed using RSM with CCD. A CCD was applied in this study to investigate the combined effects of two independent variables, i.e. composition of the cutting fluid ( $X_1$ ) and depth of cut ( $X_2$ ) on machining performance as shown in Table 1. This design is a part of RSM, which allows for the development of a second-order regression model to evaluate linear, interaction, and quadratic effects of the factors. The CCD employed in this experiment consisted of 14 runs, including factorial points, axial (star) points, and center points. The factorial points were set at low and high levels of each factor (composition: 10% and 30%; depth of cut: 0.5 mm and 1.5 mm), while the axial points extended beyond these ranges to capture potential curvature in the response surface (composition: 5.9% and 34.1%; depth of cut: 0.3 mm and 1.7 mm). Center points of all configurations are at 20% composition and 1.0 mm depth of cut. These center points were then repeated six times to ensure adequate estimation of experimental error and process stability.

The results indicated that a full quadratic model provided more reliable results. The Analysis of variance (ANOVA) of the full quadratic model (Table 2) presents a high level of significance with an F-value of 10.61 and a P-value of 0.003.

**Table 2.** Analysis of variance (ANOVA) of the full quadratic model.

Source	DF	Adj SS	Adj MS	F-value	P-value
Regression	6	260.226	0.43371	10.61	0.003
Blocks	1	0.38878	0.38878	9.510	0.018
Linear	2	0.02595	0.01298	0.320	0.738
Composition	1	0.02588	0.02588	0.630	0.452
Depth of Cut	1	0.00007	0.00007	0.000	0.967
Square	2	218.551	109.275	26.73	0.001
Composition <sup>2</sup>	1	215.119	21.1190	52.62	0.000
Depth of Cut <sup>2</sup>	1	0.08851	0.08851	2.170	0.185
2-Way Interaction	1	0.00203	0.00203	0.050	0.830
Error	7	0.28616	0.04088		
Lack-of-Fit	3	0.17834	0.05945	2.210	0.230
Pure Error	4	0.10783	0.02696		
Total	13	288.843			

The regression coefficients show that while the depth of cut had a negligible effect on surface roughness ( $P = 0.967$ ), the quadratic term for composition was highly significant ( $P = 0.000$ ). This phenomenon indicates that the optimal composition of Kesambi oil has a more substantial influence on surface quality than the depth of cut. The optimal configurations were found at a Kesambi oil composition of 19.57% and a depth of cut of 0.99 mm, yielding a surface roughness of 3.61  $\mu\text{m}$  (Table 1). This value closely matched the empirical model prediction of 3.59  $\mu\text{m}$ , demonstrating the model's accuracy in predicting surface roughness outcomes as shown in Figure 1.

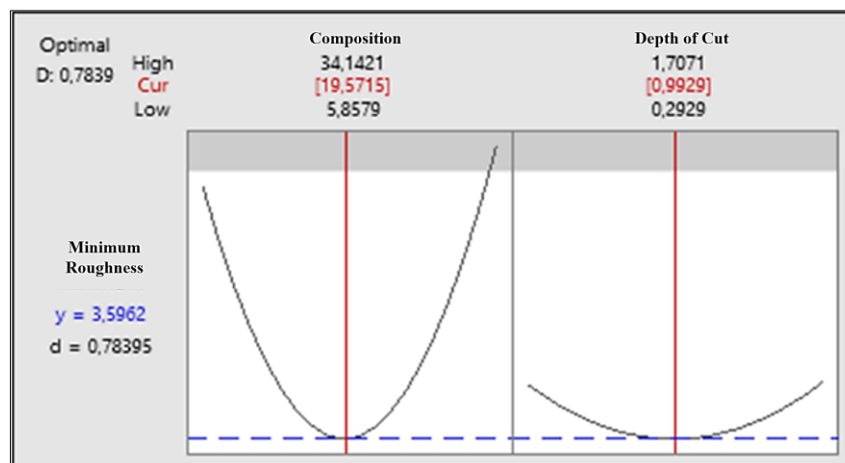


Fig. 1. Optimization plot showing the effect of composition and depth of cut on surface roughness.

### 3. Model Prediction

Based on the full quadratic regression model derived from the RSM analysis, the empirical model predicting surface roughness ( $R_a$ ) can be expressed in Eq. (1).

$$Y = 5.985 - 0.2057(X_1) - 0.780(X_2) + 0.005397(X_1^2) + 0.438(X_2^2) - 0.0045(X_1X_2) \dots (1)$$

where  $Y$  represents the predicted surface roughness ( $R_a$ ,  $\mu\text{m}$ ),  $X_1$  is the composition of Kesambi oil (%),  $X_2$  is the depth of cut (mm).

Using this model, predictions were made for surface roughness across different combinations of cutting fluid compositions and depths of cut. For instance, at the optimal condition of 19.57% Kesambi oil and a depth of cut of 0.99 mm, the predicted surface roughness was calculated to be 3.59  $\mu\text{m}$ , which closely aligns with the experimentally observed value of 3.61  $\mu\text{m}$ .

The accuracy of the model is supported by a high coefficient of determination ( $R^2 = 90.09\%$ ), indicating that 90.09% of the variability in surface roughness can be explained by the regression model. The adjusted  $R^2$  of 81.60% further confirms that the model remains statistically reliable after accounting for the number of predictors. However, the predicted  $R^2$  is considerably lower (43.56%), suggesting that while the model fits the experimental data well, its ability to generalize to new or unseen conditions may be limited. This discrepancy may be attributed to several factors. First, the relatively small number of experimental runs and inherent variability in machining processes (e.g., tool-workpiece interaction, chip formation irregularities) can introduce noise that affects predictive capability. Second, the presence of higher-order interactions or curvature effects not fully captured in the current quadratic model may also reduce predictive accuracy. Despite this, the model is still considered statistically acceptable for identifying trends and understanding factor influences within the tested range. Efforts to improve predictive  $R^2$  could include increasing the number of experimental trials or exploring alternative model structures.

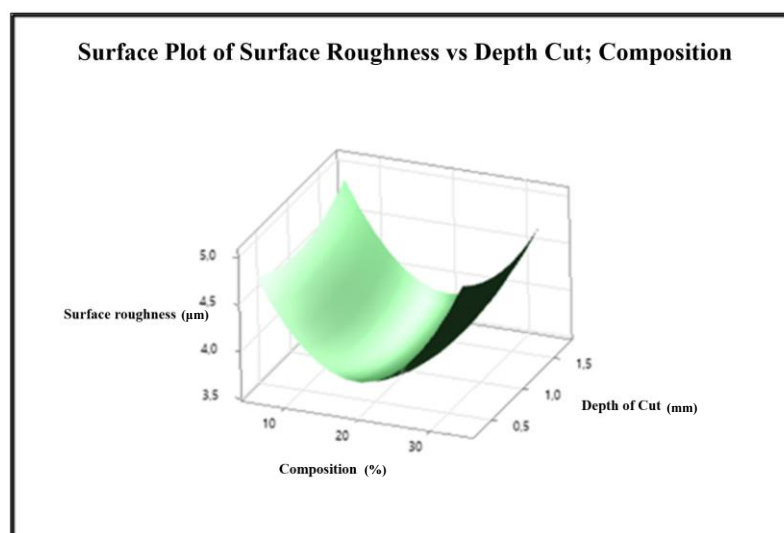


Fig. 2. Surface plot of the full quadratic model

These graphical representations further illustrate the interaction between Kesambi oil composition and depth of cut on surface roughness. The surface plot (Figure 2) and contour plot (Figure 3) show that lower surface roughness is achieved when the oil composition is around 20% and the depth of cut is approximately 1.0 mm. This confirms the empirical model's prediction and highlights the critical role of optimizing bio-cutting fluid composition in enhancing machining performance.

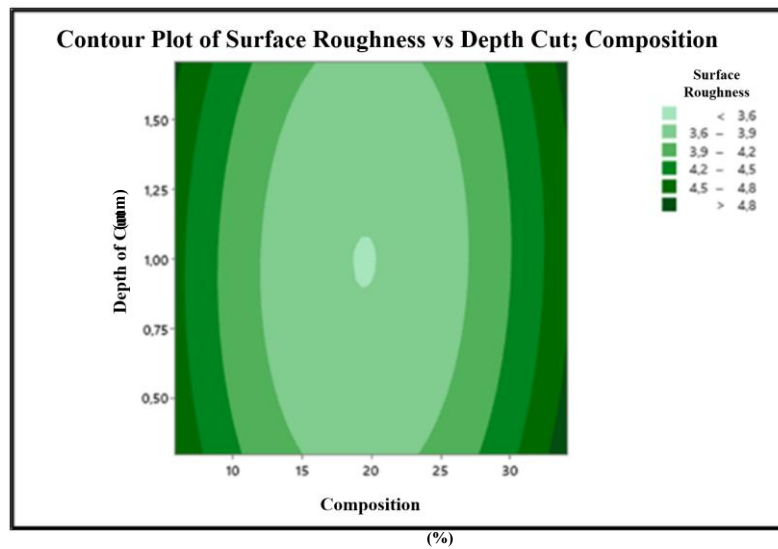


Fig. 3. Contour plot of surface roughness response

#### 4. Chip Geometry and FTIR Analysis

Chip formation and geometry were qualitatively analyzed to evaluate the influence of the bio-cutting fluid (Kesambi oil) on the turning process. Visual observations focused on chip shape, curl, continuity, and surface striation features under both dry and lubricated conditions.

As shown in Figure 4(a), the chips produced under Kesambi oil application appeared longer, less curled, and exhibited more spaced-out and uniform striations. These characteristics indicate more stable shear deformation and improved lubrication at the tool–chip interface. Similar chip features have been reported when using vegetable-based cutting fluids, which help reduce cutting temperature and modify chip morphology by promoting smoother chip flow [14]-[16]. In contrast, Figure 4(b) shows chips produced under dry cutting conditions, which were generally shorter, tightly curled, and had closely spaced, irregular striations. This morphology is commonly associated with elevated friction, high interface temperature, and severe plastic deformation during cutting [17], [18].

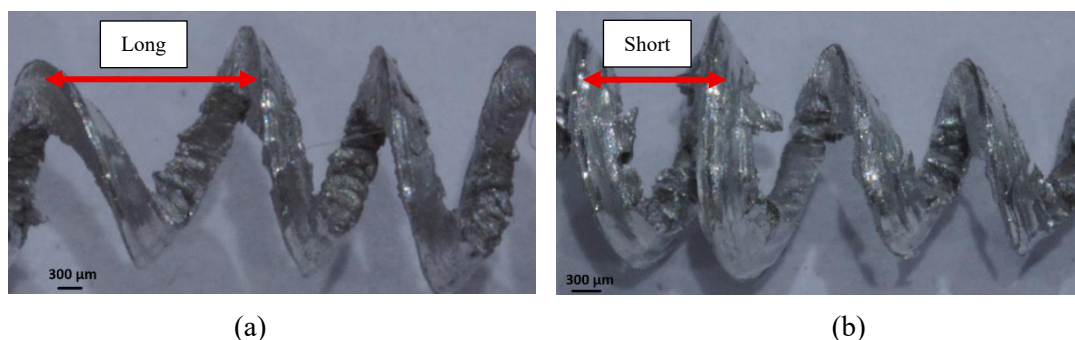


Fig. 4. Visualization of chip morphology produced under (a) optimization using Kesambi oil, (b) Dry cutting

The observation of spaced-out striations in the Kesambi oil condition (Figure 4(a)) is consistent with findings from other studies, which suggest that such features can be attributed to the formation of a protective boundary film at the tool–chip interface. Several authors have reported that vegetable oils, due to their polar triglyceride content, tend to

adsorb onto hot metal surfaces during machining, forming a tribochemical film that reduces metal-to-metal contact and alters chip flow behavior [19]-[22]. This boundary layer serves as a lubricant and thermal barrier, which improves cutting performance and tool life.

Although no quantitative surface or chemical analysis was performed in the present study, the observed chip geometry and striation characteristics strongly support the hypothesis that Kesambi oil promotes more effective lubrication and surface protection through such mechanisms. This is further supported by recent studies on bio-based lubrication, which demonstrated improved tribological behavior and chip control in machining applications using green cutting fluids [23], [24].

FTIR analysis confirmed the presence of secondary alcohol functional groups (C-O stretching) at  $1116.72\text{ cm}^{-1}$  in the optimized samples, indicating the formation of a protective film on the Al-6061 surface due to the interaction of Kesambi oil with the workpiece. This film was absent in the dry machining condition, where ester bonds were detected instead (Figure 5). This further supports the role of Kesambi oil in enhancing lubrication and surface protection during machining.

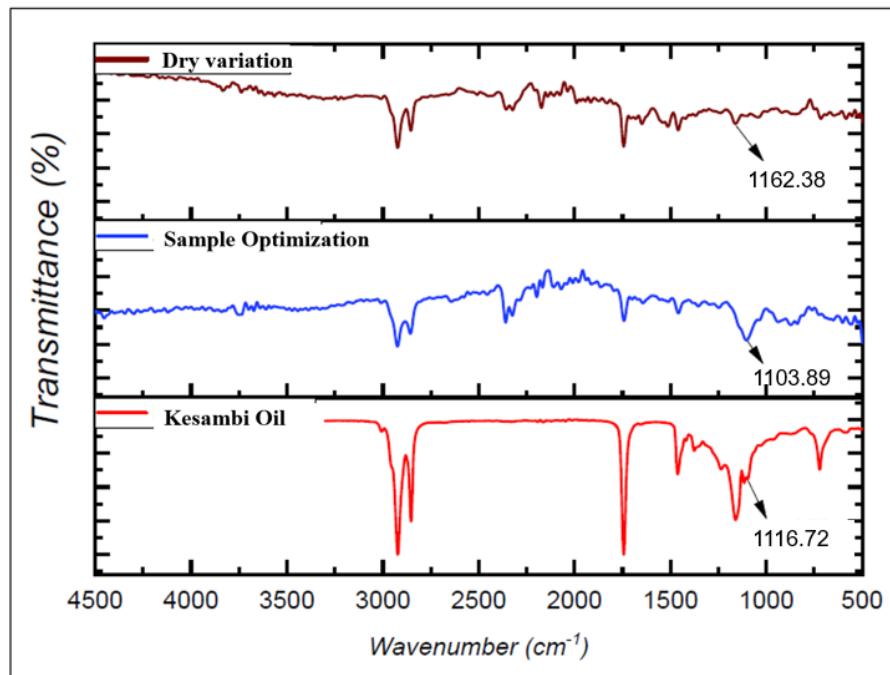


Fig. 5. FTIR spectra of dry variation, optimized sample, and pure Kesambi oil, showing differences in transmittance and peak positions around  $1162.38\text{ cm}^{-1}$ ,  $1103.89\text{ cm}^{-1}$ , and  $1116.72\text{ cm}^{-1}$ , which indicate changes in chemical composition.

## 5. Discussion

*Schleichera oleosa*, also known as Kusum or Kesambi, is commonly found across southern and southeastern Asia [25]. The results showed that the use of Kesambi oil contributed to reducing the surface roughness values compared with dry machining conditions. The lowest surface roughness of  $3.303\text{ }\mu\text{m}$  was obtained at a condition of 20% Kesambi oil and a depth of cut of 1.0 mm, while the highest surface roughness of  $4.660\text{ }\mu\text{m}$  was obtained under dry cutting conditions. This result is parallel with previous studies, which reported that bio-based cutting fluids provide better lubrication and cooling properties due to their high flash point and viscosity [10]-[11]. The performance of Kesambi oil

indicates promising potential based on the improvement over dry machining. However, direct comparison with petroleum-based cutting fluids was not included in this study. This behavior implies that Kesambi oil can reduce the cutting temperatures and friction, leading to finer surface finishes.

The full quadratic regression model exhibits a high  $R^2$  value of 90.09%. This value indicates that the model can accurately predict the surface roughness values for different configurations, which is consistent with the findings of Rao [6]. The significance of the quadratic terms for Kesambi oil composition ( $P = 0.000$ ) highlights the importance of fluid composition to maximize performance [12].

The model produced by RSM indicated that the composition of Kesambi oil has more significant effect compared to the depth of cut. Srikant and Sharma [10] and Varadarajan *et al.* [13] revealed the significance of controlling cutting fluid composition to reduce friction and enhance good lubrication in cutting operations. Furthermore, the predicted model indicates that the surface roughness of  $3.59 \mu\text{m}$  closely matches with the experimental value of  $3.61 \mu\text{m}$ . The visual analysis of chip geometry shows that using Kesambi oil produced longer, finer chips with smoother surfaces compared to dry machining. This condition indicates that the Kesambi oil lowers friction at the tool-workpiece interface. This led to low thermal impact and more effective cutting. Sharma *et al.* [26] also found that using vegetable-based oils during turning operations improved chip formation.

The FTIR analysis provided further insight into the chemical interactions between Kesambi oil and the Al-6061 surface [27] and to determine molecular fingerprints, as well as to identify various components contained in an emulsion [28]. A visible peak at wave number of  $1117.72 \text{ cm}^{-1}$  represents the secondary alcohol groups (C-O stretching) in the FTIR spectra. This means that the formation of a lubricating film on the workpiece surface reduces direct contact between the tool and workpiece [29]. In contrast, the absence of mentioned C-O group in dry machining conditions explains the unsatisfactory surface roughness and chip quality observed in this study.

The results demonstrate that Kesambi oil can be a potential alternative to conventional petroleum-based cutting fluids, which are biodegradable, non-toxic, and reduce the dependency on non-renewable resources [30]. The study provides a comprehensive investigation of Kesambi oil's performance in turning Al-6061 and filling the gap in the literature on non-edible bio-based cutting fluids. Moreover, Kesambi oil can be beneficial to large-scale industrial use, particularly in the aerospace and automotive sectors where Al-6061 is commonly used [31].

#### IV. Conclusions

This study shows the potential of Kesambi oil as a sustainable bio-based cutting fluid for improving surface quality during the turning of Aluminium 6061. The Kesambi oil composition and cutting parameters are optimized using Response Surface Methodology (RSM) and Central Composite Design (CCD). The composition of Kesambi oil at 19.57% and a cutting depth of 0.99 mm produced the most optimal surface roughness of  $3.61 \mu\text{m}$ . This value is very consistent with the model prediction of  $3.59 \mu\text{m}$ . In addition, Kesambi oil can form a lubricating layer that reduces friction during machining. This study demonstrates that Kesambi oil can support the transition toward sustainable manufacturing by offering an environmentally friendly alternative to petroleum-based cutting fluids. Although these results are promising, this study is still limited to short-term machining tests and has not evaluated tool wear or thermal effects, which are also critical considerations in industry.

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