Development and assessment of African star seed (*Chrysophyllum albidum*) oil-based cutting fluid in turning AA6061 using Taguchi grey relational approach

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Abstract

The conventional cutting fluid which is mineral oil-based has been used in numerous cutting operations which require the removal of materials. The negative effect of mineral-based oil is of great concern. This includes skin irritation and respiratory problems for machine operators, and contamination of soil and water when poorly discharged into the environment. A viable alternative must be developed which will be human and environmentally friendly. The introduction of vegetable oil can be a good alternative. Moreover, this will give room for the mixture which will result in obtaining oil that will be performed efficiently in machining and be environmentally friendly. Oils for these operations can be extracted from non-edible vegetable seeds that are deemed unfit for human consumption and refined into metalworking oil for machining. Because the demand for vegetable oils for food has risen in recent years, it is no longer viable to justify their use in machining. As a result, the current research focuses on the use of non-edible oilseeds for machining. African star oil was used as a coolant in the machining of 6061 aluminum alloy at various spindle speeds, feed rates, and cut depths. Parameters such as surface roughness and cutting temperature were measured in the evaluation for the developed African star oil, mineral oil, and dry machining environments. African star oil has demonstrated by its functionality that it can machine AA6061 with the same efficiency as a conventional cutting fluid and much better than dry machining. African star oil as cutting fluid improved surface quality and demonstrated efficient cooling behavior at the workpiece-tool interface.

Keywords: Aluminium 6061 alloy**,** African star oil, Cutting temperature, Surface roughness, Mineral oil

1 Introduction

Cutting fluid plays a crucial role in the machining processes by acting as both a lubricant and a coolant [1]. By eliminating the excessive heat generated during the cutting operation and lowering friction at the tool chip boundaries, the application of cutting fluid enhances the overall performance of a machining operation. However, the danger posed to the environment and the operators' health by regularly using mineral oil and synthetic oil-based cutting fluids made researchers pay close attention to the adoption of eco-friendly cutting fluids. Under these constraints, the use of cutting fluids based on vegetable oil has been established as a suitable substitute. Due to their environmental friendliness, sustainability, and lack of toxicity, vegetable oils are frequently preferred replacements for oils made from petroleum. Vegetable oil has a high flash point, which is required for machining operations. Due to their higher flash point, vegetable oils are more suitable for use in machining processes that entail high temperatures [2]. The density of environmentally friendly cutting fluids is comparable to that of synthetic and mineral coolants for lubrication and cooling.

The machining characteristics of cutting fluids based on vegetable oil have been the subject of numerous studies. On AISI D2 steel, Sharma and Sidhu [3] contrasted dry machining and near-dry machining using vegetable oil. The findings demonstrated that near-dry machining reduced surface roughness and work-tool contact temperatures. At greater speeds, surface roughness was further diminished. Li *et al*. [4] investigated the cooling performance of different vegetable oils in the MQL grinding of a high-temperature nickel-base alloy, including palm oil, peanut oil, sunflower oil, corn oil, rapeseed oil, soybean oil, and castor oil. The authors were able to determine that palm oil was the best base oil among the seven vegetable oils since it had the lowest grinding temperature, second-lowest grinding force, and least energy ratio coefficient. This is mostly due to the stronger lubricating effects of vegetable oils with higher viscosities, which can greatly lessen the grinding force. The relevant theories for the use of palm oil in the cutting field were provided by this research. According to Nizamuddin *et al*. [5], when AISI 1045 steel was cut orthogonally, the Karanja-based cutting fluid extended tool life by lowering chip thickness by 11%. Lawal *et al* [6] investigated the efficiency of coconut oil in the turning process of AISI 304 austenitic stainless steel with a carbide tool. They noted that the coconut oil substantially decreased tool wear and enhanced surface roughness by an average of 14%. In terms of surface roughness, Rahim and Sasahara [7] assessed the effectiveness of palm oil and synthetic ester as cutting fluids during the MQL turning of GH169 alloy. After machining with palm oil as base oil, better surface roughness, surface defect, sub-surface deformation, microhardness, and other workpiece attributes were attained. Revankar *et al*. [8] investigated the effects of different cooling techniques, including MQL (palm oil), flooding, and dry cutting on the surface roughness and hardness of Ti-6Al4V alloy during turning. When compared to flood cooling and dry machining, MQL better explained the reduced surface roughness. Singh *et al*. [9] conducted studies on the effect of vegetable and mineral oils on surface roughness during EN31 steel turning in dry and MQL conditions. In terms of surface finish, vegetable oil was shown to be better compared to mineral oil. In comparison to mineral oil, vegetable oil reduced surface roughness by about 1-10%. Majak *et al*. [10] employed sunflower, palm, and coconut oils with AISI 304 stainless steel as the cutting medium in a test to evaluate the surface finish and chip compression ratio in MQL turning. Sunflower oil outperformed coconut and palm oil as cutting oils in terms of lowering chip compression ratio and surface roughness. Lawal *et al*. [11] investigated the efficacy of three vegetable oils, two separate vegetable oils, cotton seeds and palm kernel, and one commercial kind of cutting fluid (mineral), in reducing cutting forces and surface roughness during AISI 4340 steel turning with a coated carbide tool. The performance evaluation of seed oils and mineral oils was examined, and the results showed that palm kernel and cottonseed cutting fluids were significantly more effective than mineral oils. Stefanescu *et al*. [12] compared the lubricant capacity of rape seed oil to that of conventional mineral oil. According to the findings, rape seed oil has the potential to be employed in commercial applications. Du et al. [30] tested the drilling ability of AISI 316L stainless steel using standard high-speed steel-cobalt tools with six cutting fluids (standard mineral oil and five vegetable oils, i.e., blending of both rapeseed-ester-meadowfoam oils and rapeseed-ester oils). Performance indicators such as cutting forces, chip formation, tool wear, and tool life were investigated. Vegetable cutting oil resulted in better outcomes than mineral oil because it enhanced tool life by 177% and decreased thrust power by 7%. Xavior and Adithan [13] evaluated the efficiency of coconut oil when using a carbide tool to process AISI 304 steel. In comparison to mineral oil, they discovered that coconut oil minimized tool wear and enhanced surface finish.

On the contrary, improving the cutting parameter can help any production process work better. The Taguchi technique is one of the reliable designs that has been employed for determining the best cutting parameter selections in the event of single response optimization in any product or process design. Zhang *et al*., [14] evaluated an experimental soybean-based cutting fluid with dry and petroleum-based cutting fluids in turning operations of E52100 chromium-alloy steel. An L_9 (3^4) Taguchi design was considered for experimentation. Analysis of the study results revealed that both cutting fluids were equally effective in reducing surface roughness and that the soya-based cutting fluid outperformed the petroleum-based alternative in terms of tool wear. Dennison *et al*. [15] examined the impact of near-dry machining on the surface quality obtained during milling of AISI 1045 metallic materials using environmentally friendly non-edible unprocessed oils such as castor oil, cottonseed oil, and neem oil, and conventional mineral oil emulsion cutting fluid. The test was planned using Taguchi's L_9 (3^4) orthogonal array. The results showed that machining in a near-dry environment with eco-friendly cutting fluids resulted in better product surface quality than using mineral oil. Siti and Yap [16] studied the effect of vegetable oil-based lubricants on surface roughness during the milling of mild steel. The response surface methodology and ANOVA approaches were used to investigate the relationship between cutting variables such as depth of cut, spindle speed, feed rate, and lubricants. Box-Behnken design was employed to optimize surface roughness. The surface roughness of sunflower oil was 0.457 m, which was lower than the surface roughness of synthetic oil, which was 0.679 m. In turning an AISI 1030 steel workpiece, Abutu *et al*. [17] used indigenously available palm kernel oil as a cutting fluid. To characterize and subsequently formulate vegetable oil, the full factorial L_{16} (2^4) design technique was applied. The cutting temperatures, material removal rate, and surface roughness of the produced vegetable and mineral-oil-based cutting fluids were investigated using grey relational analysis and Behnken's design technique. According to the GRA findings, the ideal turning conditions for palm kernel-oil-based cutting fluid were a depth of cut of 1.5 mm, a feed rate of 0.3 mm/rev, and a cutting speed of 600 rev/min.

As previously stated, researchers have used the Taguchi technique and grey relational analysis rather well for experimental design and multi-response optimization in the analysis of different vegetable oil as cutting fluids but the use of African star oil as metalworking fluids has not been reported. This study, therefore, aims to employ African star oil as cutting fluids in the machining of AA6061 aluminum alloy. To plan the trials in turning AA6061 aluminum alloy, this study used a Taguchi L_9 orthogonal array. Three levels for each of the three parameters— feed rate, spindle speed, and depth of cut—were included in the experimental setup. The multi-response optimization of cutting parameters was demonstrated in this study via Taguchi-based GRA to effectively reduce surface roughness and cutting temperature.

2. Materials and Methods

Based on the aims of the research outlined in chapter one, the methodology is separated into two parts. The two parts are summarized below. (1) Seed collection, oil extraction and characterization, and emulsion formation for cutting fluids. (2) Acquisition of workpiece materials and cutting tools, as well as machining experiments.

2.1 Seed Samples Collection and Description

African Star Seed was purchased at Oja-Oba Market, Ado- Ekiti, Ekiti State, Southwestern part of Nigeria. The total quantity of seeds purchased was 40 kg. The African star apple is a tropical African fruit tree that grows in forests. It is a wild plant that belongs to the Sapotaceae family, which has 800 other species and accounts for over half of the order. The fruits are not plucked from the tree; instead, they are allowed to ripen on the forest floor before being handpicked by the farmers. *Chrysophyllum albidum* contains some flavonoid, phenol, and high oxidant value, according to an examination of its nutritional value and antioxidant. The fruit has a variety of medical uses, including treating bruises, sprains, and wounds, as well as stopping bleeding. Fig. 1 depicts a photographic picture of African star apples and their seeds used in this study.

The seeds were acquired unshelled from the market. Before grinding, the seeds were unshelled, and the pulp was sun-dried for several days. A laboratory mill was used to grind the dry seeds. A portion of the seeds was placed in a pipette and then placed in the Soxhlet apparatus for chemical extraction [18]. A round bottom flask holding 99 percent analytical grade n-Hexane was equipped with a bottomed flask at the top. The oil from the African star apple was extracted in a Soxhlet extractor with n-Hexane (boiling range: 55-65°C) and then tested for physicochemical properties. In this research, extracted oil will be formulated subsequently into eco-friendly cutting fluids and further used in the machining of Aluminium 6061 alloy on the Lathe machine. The apparatus was positioned on a heating unit set to around 55°C to 65°C, and the condensing liquid gently trickled into the cup containing the ground seeds. The extract is sucked into the siphon duct through the thimble's small holes. For 6 - 8 hours, this procedure was permitted to continue. The extraction was then boiled in a rotary vacuum evaporator to retrieve the solvent, keeping the extracted oil intact. Chemical extracting of seed oils was conducted following the AOAC norm [19]. Crude oils were obtained using a 5-liter rounded bottom flask, a Soxhlet system, and analytical grade n-hexane with a heating range of 50-65 ° C. The harvested oils were examined, the yield was determined, and the oils were appropriately kept at room temperature for subsequent testing. The photographic image of the extraction process is shown in Fig. 2.

Fig. 1. (a) African star apple (b) African star seeds before Unshelling (c) African star seeds after Unshelling process

Fig. 2. Extraction process of African star seed oil using Soxhlet extractor with n-Hexane

African star seed oil was studied using crude oil extracts to determine its physical and chemical properties. This was done to determine feasible conditions for the composition of cutting fluid. Various tests were performed on the crude oils recovered from the sample. The tests include density, peroxide value (PV), iodine value (IV), saponification value (SV), acid value (AV), specific gravity (SG), and kinematic viscosity (KV). Table 1 shows the summary of selected physiochemical properties considered in this study. Cutting fluids developed in this study were evaluated at the emulsion cutting fluid level. By combining distilled water, additives, and vegetable oil, an emulsion-cutting fluid was produced. Biocides, anti-foam agents, emulsifying agents, and anti-corrosive agents are among the additives employed in the compositions. The additives employed in the composition of emulsion cutting fluids were neither damaging to the environment nor the equipment operators.

Table 1: Summary of selected physiochemical parameters

Parameter	Equation	Definition	Eq. No.
SG	$\frac{W_o}{W_{evw}}$	W_o = weight of oil, W_{evw} = an equal volume of water	1
AV	$\frac{(56.1 \times M \times V)}{W}$	$V =$ KOH concentration (mL), W = sample weight, $M =$ the molar concentration of KOH (M)	2
SV	$\frac{(B-S) \times M \times 56.1}{W}$	$(B - S) =$ difference between the volume of HCl solution used for the blank run and the tested sample, in mL; M is the molarity of a HCl solution, in mol $L-1$; 56.1= molecular weight of KOH in $g \cdot mol^{-1}$; $W =$ weight of the sample, in g .	3

IV	$\frac{[(B-S)\times N\times 12.69]}{W}$	$(B-S)$ = difference between the volumes mL of sodium thiosulfate required for the blank and the sample, respectively. $N =$ normality of sodium thiosulfate solution in Eq/L . $12.69 =$ conversion factor from mEq sodium thiosulfate to grams of iodine (the molecular weight of iodine $=126.9\ g\cdot mol^{-1}$; $W =$ weight of the sample in grams.	4
PV	$\frac{[1000(V_0-V_1)\times M]}{W}$	M =Thiosulphate $Na_2S_2O_3$ molarity, W = sample mass (1g), $V_0 =$ amount of Thiosulphate used in the test (mm) $V_1 =$, and Thiosulphate vegetable oil (ml) utilized in the blank.	5
KV	$Adt-\frac{Bd}{t}$	A and B = constants, t = amount of time in seconds; Viscosity expressed in centipoises *(cP), d* = Density in *g/ml*	6

2.2 Collection of Workpiece Material and Cutting Tools

A scrapyard in Ado-Ekiti supplied one complete-length workpiece material with specifications of 55 mm diameter and 800 mm length. The length of the workpiece was then lowered to 200 mm, but the diameter was reduced to 50 mm. This was needed to preserve a 4 to 1 proportion of cylinder cutting length to starting diameter of the workpiece in ensuring the workpiece/chuck/cutting force rigidity necessary [11, 20]. It was revealed by spark analysis conducted that the aluminum alloy material has 0.1 % Zn, 0.02 % Ti, 0.2 % Cr, 0.3 % Cu, 0.35 % Fe, 0.60 % Si, 0.07 % Mn, 1.0 % Mg and 97.36 % Al and this is aluminum alloy 6061 composition. The cutting tools used for the machining were tungsten carbide insert tools because of their longevity and recommendation by the workpiece makers. A *GH-1640* Geared Head Precision Lathe was used for the machining process. The machine in consideration is a conventional machine tool. The cutting fluid application technique adopted in this research is the flooding cooling technique.

2.3 Selection of Cutting Parameters

The experimental procedure was established on the Taguchi technique of DOE, and three cutting variables namely, feed rate, depth of cut, and spindle speed were tested. As a result, three input variables and three levels were considered for each parameter, as indicated in Table 2. Taguchi selected the L_9 (3^3) orthogonal array for investigation in a 3-level test. As a result, the Taguchi L_9 orthogonal array of research setup was employed to conduct nine cutting experiments. Each cutting fluid examination was done on a new workpiece material and cutting insert. To avoid any effect of non - uniformity on the test results, the rusted layers were eliminated using a fresh cutting insert before actual machining started. Each side of the samples was pre-machined to a thickness of 2 mm. Each cutting test is conducted with a 120 mm cutting length. Table 3 was used to assess each of the three cutting fluids generated from African star seed oil as well as the market cutting fluid (soluble oil). As a result, each cutting fluid was evaluated through nine experimental tests. For the examination of each cutting fluid, new workpiece material and cutting inserts were employed.

2.4 Determination of Process Parameters

By using a portable surface roughness tester, model SRT-6100, the work material's surface roughness *(Ra)* was measured. Three random measurements were taken along the length of the workpiece for each sample, and the average value was used in the study. An in-depth overview of the SRT-6100 is shown in Fig. 3 (a). A Dual Channel Thermocouple Thermometer PROSTER, model PST095, was used to assess the cutting temperature. Fig. 3 (b) depicts the pictorial view. During cutting, the probing of the thermometer was pointed toward the tool-chip interface. The thermometer was carefully maintained at a position of roughly 5 cm from the tool/chip interface. For every sample, three data were measured, and the mean result was recorded.

Fig. 3. (a) Surface roughness tester (SRT -6100) taking readings on the sample (b) Cutting temperature tester (Dual Channel Thermocouple Thermometer)

2.5 Determination of Optimal Cutting Parameters

An optimization strategy in machining operations was thought to play a critical role in the continuous quality improvement of product/process quality attributes. Modeling input-output and operational parameter relationships, as well as determining optimal cutting conditions, are all part of this process. For cutting optimization techniques, the average values for cutting temperature were considered. Minitab16 statistical analysis program with the following tools was used to optimize cutting temperature, surface roughness, and the impact of cutting conditions for each cutting fluid. (i) Taguchi robust approach design (ii) Grey relational analysis (iii) Regression models. Under flooded cooling settings, Taguchi's robust design technique was effectively utilized to discover the optimum parameters to minimize cutting temperature and surface roughness during the machining of Aluminium 6061 workpieces using emulsion African Star Seed Oil and Mineral oil emulsion cutting fluids. The analysis of variance is used to determine the impact and effectiveness of each cutting variable throughout the metal cutting.

A system that has some existing facts and some unknown information is referred to as a grey system. Grey systems will present a range of possible options because there is always uncertainty. Based on this finding, GRA may be effectively used to solve the complex dependencies between the specified performance factors. The GRG is defined favorably as an indication of numerous performance qualities for assessment in this study. GRA has emerged as a useful method for analyzing processes with many performance attributes in recent times. The intricate multi-response optimization issue in GRA may be condensed into the optimization of a single-response GRG. In Table 4, the process for getting the GRG is described in greater depth.

Table 2. Cutting variables and their levels

Factor	**Level 1**	**Level 2**	**Level 3**
Spindle speed (rev/min)	415	870	1400
Feed rate (mm/rev)	0.1	0.15	0.20
Depth of cut (mm)	1.0	1.5	2.0

Table 3. Standard L_9 (3^3) Orthogonal Array

	Column			**Cutting Parameter**		
Experiment No	**1**	**2**	**3**	**Spindle Speed (rev/min)**	**Feed Rate (mm/min)**	**Depth of Cut (mm)**
1	1	1	1	415	0.10	2.0
2	1	2	2	415	0.15	1.5
3	1	3	3	415	0.20	1.0
4	2	1	2	870	0.10	2.0
5	2	2	3	870	0.15	1.5
6	2	3	1	870	0.20	1.0
7	3	1	3	1400	0.10	2.0
8	3	2	1	1400	0.15	1.5
9	3	3	2	1400	0.20	1.0

Table 4. A guide to conducting an effective grey relational analysis [20]

Step	Action
1.	The dataset should first be normalized to avoid utilizing various metrics and minimize unpredictability. Because the variability of one dataset varies from that of other datasets, it is usually required. By computing a suitable result from the true state, the cluster is constructed from 0 to 1 [21]. In essence, it is a method of translating actual information to record. Eq.7 is used to standardize the reaction into a suitable level utilizing smaller-is-better criteria if the output needs to be lowered. $y^{*}{}_{j}(n) = \dfrac{\max y_j(n) - y_j(n)}{\max y_j(n) - \min y_j(n)}$ (7) where n is the number of responses and p is the number of experimental findings; j = 1,, u; n = 1,..., q. Real series is described by yj (n), the maximum value is indicated by max yj (n), the lowest value is expressed by min yj (n), and series are defined by y*j (n) following output pre-processing, where y is the desired value [21, 22].
2.	The normalized data are utilized to calculate the grey relational coefficient, $\varphi_j(n)$, using Eq. 8.

$$\varphi_j(n) = \frac{\chi_{\min} + \varphi\chi_{\max}}{\chi_{\circ j}(n) + \varphi\chi_{\max}} \tag{8}$$

where χ_{oj} is the divergence series of the reference series and the comparability series and $\chi_{oj} = \left\| y_o(n) - y_j(n) \right\|$.

where y_{j}(n) is the comparability series and y_{o}(n) is the reference series. The absolute values χ_{oj} of the disparities between all series being compared are max and min, expressed as $\chi_{\max}$ and $\chi_{\min}$ respectively. The distinguishing coefficient, φ, which runs from 0 to 1, has a typical value of 0.5.

3. Using Eq. 9, the grey relational grade (GRG) is estimated:

$$\lambda_j = \frac{1}{m}\sum_{k=1}^{m}\varphi_j\left(k\right) \tag{9}$$

where m = number of response characteristics and γ_{i} = the required GRG for the j^{th} trial. The GRG is a comprehensive measurement of all attributes and indicates how similar the comparing and referencing sets by Panda *et al.*, [21]. The multiple response optimization models are reduced to one by using GRA and the Taguchi method.

4. Then, using a higher GRG, a sufficient level of operation conditions is obtained, indicating a higher level of product quality. It requires that the mean grade values for various levels of process variables be computed and presented as a mean response chart to be used. The best parameterization mixture for many selections is determined by the larger value of the mean grade values from the mean reaction chart.

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3. Results and Discussion

3.1 Physicochemical Properties of Virgin African Star Seed Oil

Table 5 shows the physiochemical characteristics of raw African star oil. The density of the obtained African star oil in this investigation was 0.9280 g/cm^3, which is like the value of 0.924 g/cm^3 published by Igbafe *et al.*, [23] and 0.937 g/cm^3 reported by Dzarma *et al.*, [24]. The acid value of a triglyceride is an indicator of its titratable acidity, which includes inputs from all the essential fatty acids that make up the glyceride molecule. Triglycerides are transformed into glycerol and fatty acids as oil triglycerides turn deteriorated, causing an increase in acid levels. Furthermore, the acid value, which considers the involvement of all the constituting fatty acids in the fat or oil, can provide more details on the acid content of triacylglycerols. The total acidity was 4.8 mg KOH/g given as an acid value. The acid value measured for African star oil is comparable to the acid values published previously in the literature for some vegetable oils. Watermelon, Jatropha, Mango, and Nicker nut oil have acid values of 3.24, 5.38, 2.89, and 3.17 mg KOH/g, respectively [25]. It was found that a low acid value is one of the most essential yardsticks for measuring and assessing the bioavailability of vegetable oils, with high values indicating a tendency for major manufacturing utilization of the vegetable oil in question. As a result, cutting fluids made from oil extracts with greater acid levels will perform better.

The saponification value is a measurement of the normal size of fatty acid in a test sample, which is determined by the molecular mass and percentage content of fatty acid constituents. The saponification value of an oil will be greater if it includes higher saturated fats as this impacts the size of the carbonyl group in the oil [26]. The saponification value of African star oil was determined to be 220 mg KOH/g. This fall in the range of various well-known oils which have been used as cutting fluids in the past. The saponification value of Nicker nut oil is 257 mg KOH/g, whereas the quantity in Jatropha oil is 173 mg KOH/g [25]. Tamanu oil nuts with an iodine value of 62.5 mg/g iodine also satisfy the iodine needs for cutting fluids. Cutting fluids are typically high-viscosity base fluids, with viscosities ranging from 15 to 50 cSt at 100 °F. Because of their greater heat transfer coefficients, high-viscosity oils speed up the evacuation of heat from the workpiece and tool interface, as well as the quick settlement of swarfs and chips from flowing oil. The kinematic viscosity value of African star oil at 40^0C was 50.32 cP, and this is close to the viscosity obtained by Jayeoye *et al*. [25] for some vegetable oils (Watermelon oil 43.3 cP, Nicker nut oil 47.9 cP, Jatropha oil 40.5 cP, Tamanu nut oil 53.1 cP, and Sandbox oil 37.9 cP). All these values fall within the acceptable range of oil that could function or act as a cutting fluid. The percentage oil yield obtained for African star oil is 10.2%. This is close to what was obtainable by Dzarma *et al*., [24]. The species employed, the soil and climate conditions, and the seed preparation could all be responsible for the reported yield discrepancies.

Table 5. Physicochemical properties of extracted African Star Seed Oil

Property	**Reported Value**
Specific gravity	0.9523
Density (g/cm^3)	0.9280
Kinematic viscosity, 40 °C (cP)	50.32
Acid value (mg KOH/g)	4.8
Saponification value (mg KOH/g)	220.0
Iodine value mg I/g	70.28
Peroxide value (mg/g)	3.62
% Oil yield	10.2

3.2 Experimental Results for Aluminium 6061 Alloy Machining with different Conditions

The results obtained for cutting temperature and surface roughness by using three machining environments namely, dry machining, mineral oil emulsion cutting fluid, and African star emulsion cutting fluid are presented in Tables 6, 7, and 8. For better comparison of the machining environments, the data is converted into charts as shown in Figs 6 and 7. It can be observed that cutting temperature and surface roughness fell within the ranges of 35.2 -45.9°C and 0.484 – 3.102 μm; 32.1– 37.3°C and 0.332-0.945 μm; 28.3-31.9°C and 0.085 – 0.641 μm for dry machining, emulsion mineral oil cutting fluid and emulsion African star seed oil cutting fluid, respectively. In general, cutting temperature and surface roughness were $39.24 \pm 3.53°C$ and $1.47 \pm 1.03 \mu m$; $34.98 \pm 1.70°C$ and $0.62 \pm 0.23 \mu m$, and $30.33 \pm 1.01°C$ and $0.347 \pm 0.23 \mu m$ for dry machining, mineral oil-based cutting fluid and African star cutting fluids, respectively. It is claimed that better metal cutting was attained, with lower surface roughness and cutting temperature. From the results of process parameters, African star seed oil cutting fluid emulsion performed exceedingly better than dry machining and mineral oil. African star seed oil cutting fluid outsmarted dry machining conditions and mineral oil in terms of both surface roughness and cutting temperature. The dry machining environment had a poor output concerning both cutting temperature and surface roughness.

Dry machining is the simplest production technology since it does not involve any cutting fluid. For effective dry machining, machining materials such as the cutting tool, workpiece material, and cutting process variables must be thoroughly studied. Cemented carbides, cermet, ceramics, polycrystalline diamond, and cubic boron nitride (CBN) for example, are the preferred material for dry cutting because of their high wear resistance and high heat hardness. Dry cutting, or machining without a fluid, is an excellent option for reducing environmental and health concerns but has failed miserably in the cylindrical turning of Aluminium 6061 alloy in this study. Furthermore, soft metals such as aluminum are not advised for dry cutting since, they generate a built-up edge during the machining operation, affecting the surface [27]. For this operation, dry machining is not a feasible option, African star seed oil-based cutting fluid is preferred. The developed African star seed oil in this study has proved to be the most promising in the turning operation of AA6061 Aluminium alloy. African star oil outperformed other machining conditions in the entire nine trials for both process parameters considered. When compared to conventional soluble oil, the effectiveness of African star oil-based cutting fluids in the cutting of aluminum has proven that they can accomplish the same operations as foreign products. They increased the surface finish and showed excellent cooling behavior at the tool/workpiece interface, reducing the chip thickness ratio observed. This is owing to the presence of surface-active chemicals and their high viscosity, which aid in the reduction of a liquid's surface energy and increase its wetting capabilities or oiliness.

Table 6. Experimental results of dry cutting

S/N	Feed Rate (mm/min)	Depth of Cut (mm)	Spindle Speed (rpm)	Cutting Temperature (°C)	Surface Roughness (μm)
1	0.10	2.0	415	35.2	2.519
2	0.15	1.5	415	36.5	3.102
3	0.20	1.0	415	35.3	2.707
4	0.10	2.0	870	40.8	1.561
5	0.15	1.5	870	38.7	0.835
6	0.20	1.0	870	38.1	0.711
7	0.10	2.0	1400	45.9	0.484
8	0.15	1.5	1400	42.6	0.671
9	0.20	1.0	1400	40.1	0.681

Table 7. Experimental results of mineral oil emulsion cutting fluid

S/N	Feed Rate (mm/min)	Depth of Cut (mm)	Spindle Speed (rpm)	Cutting Temperature (°C)	Surface Roughness (μm)
1	0.10	2.0	415	32.1	0.945
2	0.15	1.5	415	34.1	0.910
3	0.20	1.0	415	33.4	0.794
4	0.10	2.0	870	36.0	0.512
5	0.15	1.5	870	35.6	0.640

6	0.20	1.0	870	34.0	0.667
7	0.10	2.0	1400	37.3	0.358
8	0.15	1.5	1400	36.9	0.332
9	0.20	1.0	1400	35.4	0.434

Table 8. Experimental results of African star oil emulsion cutting fluid

S/N	Feed Rate (mm/min)	Depth of Cut (mm)	Spindle Speed (rpm)	Cutting Temperature (°C)	Surface Roughness (μm)
1	0.10	2.0	415	30.3	0.641
2	0.15	1.5	415	30.9	0.677
3	0.20	1.0	415	31.0	0.568
4	0.10	2.0	870	29.7	0.321
5	0.15	1.5	870	30.8	0.309
6	0.20	1.0	870	31.9	0.315
7	0.10	2.0	1400	28.3	0.109
8	0.15	1.5	1400	30.2	0.099
9	0.20	1.0	1400	29.9	0.085

Surface roughness increased rapidly as cutting depth and spindle speed increased (see Fig. 4). Higher speeds increase the cutting temperature and cutting forces acting on the tool, increasing tool wear and thereby affecting the surface quality of the manufactured AA6061 Aluminium alloy surface. Because cutting fluids flow off from the workpiece/tool interface at high-speed machining, the surface finish deteriorates as the depths of cuts and spindle speeds increase. The reaction period for chemical compound synthesis is too short, as is the time for heat convection generated at high cutting speeds. As the speed increases, there comes a point beyond which no built-up edge is generated. With increased depths of cut and feed rates, there is also a progressive increase in roughness. The sequence of enhancing surface finish for all machining environments tested is African star oil, mineral oil emulsion cutting fluid, and dry machining.

Fig. 5 depicts the temperature differences among the machining environments. The temperature steadily increased as the feed rate, spindle speed, and depth of cut were raised. In a previous article [28], it was established that cutting forces diminish with speed however since the heat generated is the resultant force and velocity, increasing speed generates more temperature. Furthermore, at low cutting speeds, the distortion in the shear zone is the most important factor influencing chip/tool interface heat, but at incredibly fast speeds, chip-tool friction is the most important factor influencing interface heat. Owing to the fatty acid content in vegetable oil, African star oil-based cutting fluid performed much better than mineral oil-based cutting fluid and dry cutting in terms of thermal reduction. The fatty acid features of African seed oil that improve its machinability are effective as boundary lubricating oil chemical interactions between the polar head of the acid molecule and the outer layer it reacts with, generating an adsorbent surface layer that is deep enough to separate the surface areas, reducing the friction [28]. Furthermore, the fatty acid content and flowability of African seed oil allowed for quicker penetration of the workpiece-tool contact, resulting in improved temperature control. The rate of temperature reduction ability obtained in this study was in the order of African star oil, mineral oil, and dry cutting when the speed was altered. Previous research on cutting fluids has revealed that their performance varies depending on their chemical constituents; for example, oil-based fluids like African star seed oil reduce friction (drag) and allows movement, resulting in a gradual decline in friction coefficient and thus power decrease, resulting in a machined component with excellent surface finish.

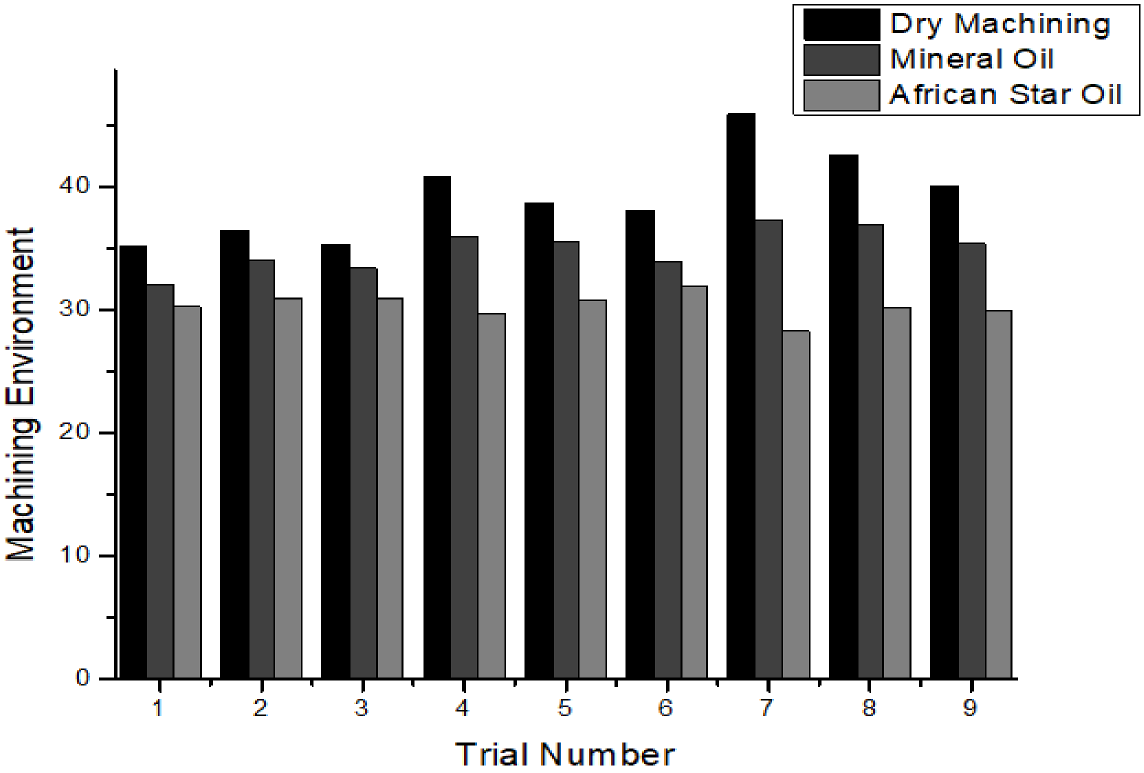

Fig. 4. Effect of various Machining Environments on Cutting Temperature of Aluminium 6061 Alloy

3.3 Computation of Multiple Response Parametric Optimizations using Grey Relation Analysis

The test results from the experiment during the turning of Aluminium alloy 6061 are shown in Tables 9, 10, and 11. The minimum and maximum values for each performance characteristic were determined during the standardization of the experimental data. The experimental findings for cutting temperature and surface roughness were normalized using Eq. (7). Tables 12, 13, and 14 show the results for the three machining environments under study as grey relational generations. Tables 15, 16, and 17 show the deviation sequence for African star oil, mineral oil, and dry cutting, respectively. To calculate the grey relational coefficients, the deviation sequence is required [20, 22].

Table 9. Experimental Results of Dry Cutting

S/N	Feed Rate (mm/min)	Depth of Cut (mm)	Spindle Speed (rev/min)	Cutting Temp. (°C)	Surface Roughness (μm)
1	0.1	2	415	35.2	2.519
2	0.15	1.5	415	36.5	3.102
3	0.2	1	415	35.3	2.707
4	0.1	2	870	40.8	1.561
5	0.15	1.5	870	38.7	0.835

6	0.2	1	870	38.1	0.711
7	0.1	2	1400	45.9	0.484
8	0.15	1.5	1400	42.6	0.671
9	0.2	1	1400	40.1	0.681
			Min	35.2	0.484
			Max	45.9	3.102

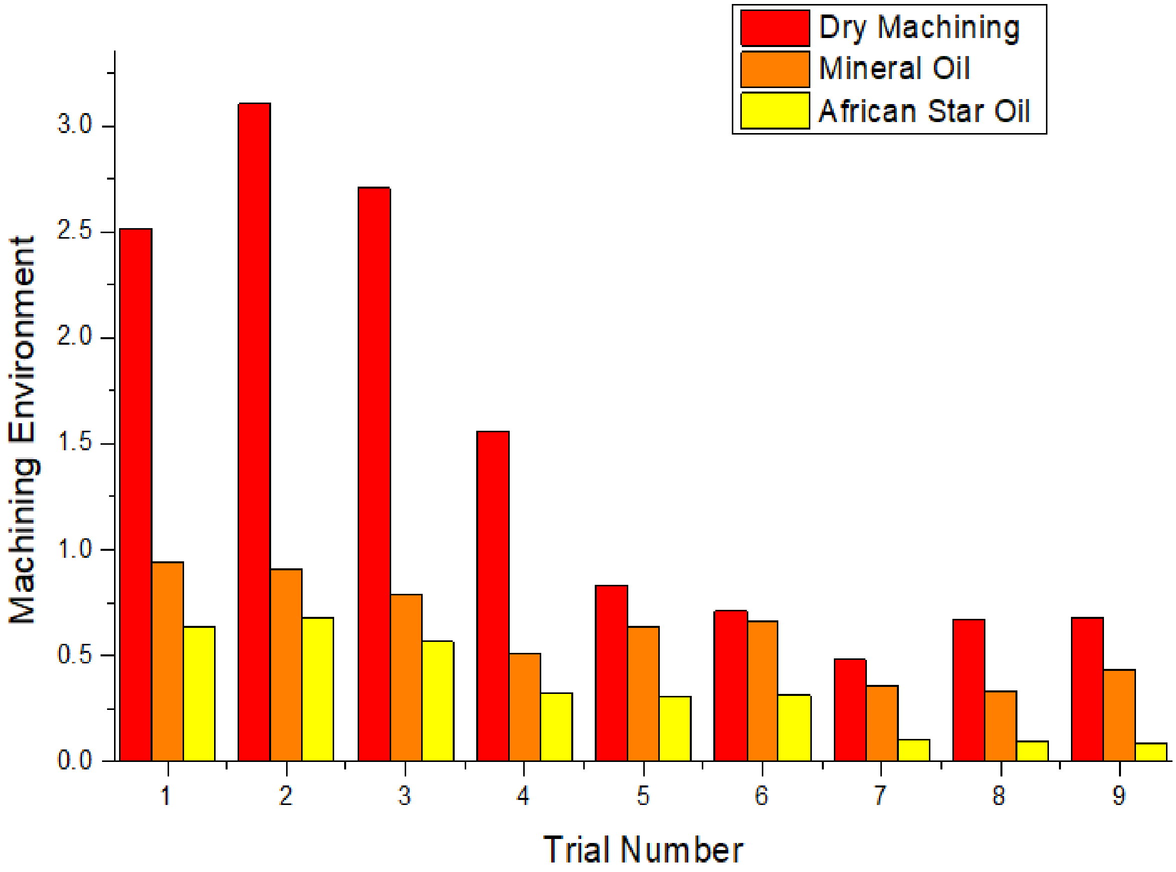

Fig. 5. Effect of various Machining Environments on Surface Roughness of Aluminium 6061 Alloy

Table 10. Experimental Results of African Star Oil Emulsion Cutting Fluid

S/N	Feed Rate (mm/min)	Depth of Cut (mm)	Spindle Speed (rev/min)	Cutting Temp. (°C)	Surface Roughness (μm)
1	0.10	2.0	415	32.1	0.945
2	0.15	1.5	415	34.1	0.910
3	0.20	1.0	415	33.4	0.794
4	0.10	2.0	870	36.0	0.512
5	0.15	1.5	870	35.6	0.640

6	0.20	1.0	870	34.0	0.667
7	0.10	2.0	1400	37.3	0.358
8	0.15	1.5	1400	36.9	0.332
9	0.20	1.0	1400	35.4	0.434
			Min	32.1	0.332
			Max	37.3	0.945

Table 11. Experimental Results of Mineral Oil Emulsion Cutting Fluid

S/N	**Feed Rate (mm/min)**	**Depth of Cut (mm)**	**Spindle Speed (rev/min)**	**Cutting Temp. (°C)**	**Surface Roughness (μm)**
1	0.1	2	415	30.3	0.641
2	0.15	1.5	415	30.9	0.677
3	0.2	1	415	31	0.568
4	0.1	2	870	29.7	0.321
5	0.15	1.5	870	30.8	0.309
6	0.2	1	870	31.9	0.315
7	0.1	2	1400	28.3	0.109
8	0.15	1.5	1400	30.2	0.099
9	0.2	1	1400	29.9	0.085
			Min	28.3	0.085
			Max	31.9	0.677

Table 12. Grey Relational Generation Values for Dry Cutting

Normalization	
Cutting Temp. (°C)	**Surface Roughness (μm)**
1.0000	0.2227
0.8785	0.0000
0.9907	0.1509
0.4766	0.5886
0.6729	0.8659
0.7290	0.9133
0.0000	1.0000
0.3084	0.9286
0.5421	0.9248

Table 13. Grey Relational Generation Values for Mineral Oil Emulsion Cutting Fluid

Normalization	
Cutting Temp. (°C)	**Surface Roughness (μm)**
1.0000	0.0000
0.6154	0.0571
0.7500	0.2463
0.2500	0.7064
0.3269	0.4976

0.6346	0.4535
0.0000	0.9576
0.0769	1.0000
0.3654	0.8336

Table 14. Grey Relational Generation Values for African Star Oil Emulsion Cutting Fluid

Normalization	
Cutting Temp. (°C)	**Surface Roughness (μm)**
0.4444	0.0608
0.2778	0.0000
0.2500	0.1841
0.6111	0.6014
0.3056	0.6216
0.0000	0.6115
1.0000	0.9595
0.4722	0.9764
0.5556	1.0000

Table 15. Deviation Sequence for Dry Cutting

Cutting Temp. (°C)	**Surface Roughness (μm)**
0.0000	0.7773
0.1215	1.0000
0.0093	0.8491
0.5234	0.4114
0.3271	0.1341
0.2710	0.0867
1.0000	0.0000
0.6916	0.0714
0.4579	0.0752

Table 16. Deviation Sequence for Mineral Oil Emulsion Cutting Fluid

Cutting Temp. (°C)	**Surface Roughness (μm)**
0.0000	1.0000
0.3846	0.9429
0.2500	0.7537
0.7500	0.2936
0.6731	0.5024
0.3654	0.5465
1.0000	0.0424
0.9231	0.0000
0.6346	0.1664

Table 17. Deviation Sequence for African Star Oil Emulsion Cutting Fluid

Cutting Temp. (°C)	**Surface Roughness (μm)**
0.5556	0.9392
0.7222	1.0000

0.7500	0.8159
0.3889	0.3986
0.6944	0.3784
1.0000	0.3885
0.0000	0.0405
0.5278	0.0236
0.4444	0.0000

The normalized data set was utilized to derive the grey relational coefficients from Eq. 8. Due to the equal weighting of the two quality descriptors, the differentiating coefficient was set at 0.5. The outcomes are shown in Tables 18, 19, and 20. The grey relational coefficients were then used to estimate the GRG using Eq. 9. Tables 18, 19, and 20 display the GRG's findings. The output is employed to evaluate the multiple responses after being reduced to a single grade.

Table 18. Grey Relational Coefficient and Grade Relational Grade for Dry Cutting

Cutting Temp. (°C)	Surface Roughness (μm)	Grade	Rank
1.0000	0.3914	0.6957	3
0.8045	0.3333	0.5689	8
0.9817	0.3706	0.6761	5
0.4886	0.5486	0.5186	9
0.6045	0.7886	0.6965	2
0.6485	0.8522	0.7503	1
0.3333	1.0000	0.6667	6
0.4196	0.8750	0.6473	7
0.5220	0.8692	0.6956	4

Table 19. Grey Relational Coefficient and Grade Relational Grade for Mineral Oil Emulsion Cutting Fluid

Cutting Temp. (°C)	Surface Roughness (μm)	Grade	Rank
1.0000	0.3333	0.6667	2
0.5652	0.3465	0.4559	9
0.6667	0.3988	0.5327	5
0.4000	0.6300	0.5150	7
0.4262	0.4988	0.4625	8
0.5778	0.4778	0.5278	6
0.3333	0.9218	0.6276	3
0.3514	1.0000	0.6757	1
0.4407	0.7503	0.5955	4

Table 20. Grey relational coefficient and grade relational grade for African Star Oil Emulsion Cutting Fluid

Cutting Temp. (°C)	Surface Roughness (μm)	Grade	Rank
0.4737	0.3474	0.4106	7
0.4091	0.3333	0.3712	9

0.4000	0.3800	0.3900	8
0.5625	0.5564	0.5594	4
0.4186	0.5692	0.4939	5
0.3333	0.5627	0.4480	6
1.0000	0.9250	0.9625	1
0.4865	0.9548	0.7207	3
0.5294	1.0000	0.7647	2

Tables 21, 22, and 23 use the GRG value to calculate the mean grey relational grade. The most significant mean GRG values in Tables 21, 22, and 23 for Dry machining, mineral oil, and African star oil, respectively, identify the optimal parametric combination. A higher-grade GRG with a higher value suggests a stronger correlation to the reference sequence. As a result, the optimal dry machining parameters for multi-responses are SS3-FR3-DOC1, or 0.6698 spindle speed, 0.7074 mm/rev feed, and 0.7074 mm depth of cut, respectively. The lower the surface roughness and cutting temperature, the bigger the mean GRG results. For turning parameters, the difference between the greatest (maximum) and lowest (minimum) mean GRG values was 0.0229 for spindle speed, 0.0804 for feed rate, and 0.0804 for depth of cut, respectively (see Table 22). This research revealed that, when compared to spindle speed, feed rate and depth of cut have the largest influence on multi-responses in turning operations with mineral oil-based cutting fluids. The importance of process factors on multi-responses is in this order: feed rate and depth of cut > spindle speed [29].

The optimal parameters for mineral oil-based cutting fluid are SS3-FR1-DOC3, or 0.6329 spindle speed, 0.6031 mm/rev feed, and 0.6031mm depth of cut, respectively, as shown in Table 23. The difference between the highest and lowest mean GRG values for turning parameters was 0.1311 for spindle speed, 0.0511 for feed rate, and 0.0717 for depth of cut. In comparison to feed rate and depth of cut, spindle speed has the most significant impact on multi-responses in mineral oil turning operations, according to this study. The sequence of the effectiveness of process parameters on multi-responses is spindle speed > feed rate > depth of cut. The optimal parameters for African star oil-based cutting fluid are SS3-FR1-DOC3, or 0.6329 spindle speed, 0.6031 mm/rev feed, and 0.6031mm depth of cut, respectively, as shown in Table 24. The difference between the highest and lowest mean GRG values for turning parameters was 0.8160 for spindle speed, 0.6442 for feed rate, and 0.6442 for depth of cut. When compared to feed rate and depth of cut, spindle speed has the most significant impact on multi-responses in turning operations using African star oi cutting fluid, according to this study. The order of effectiveness of process parameters on multi-responses is spindle speed > feed rate = depth of cut [29-30].

Table 22. Main Effects on Mean GRG for Dry Machining

Parameter	Level 1	Level 2	Level 3	Max-Min	Rank
Feed rate	0.6270	0.6376	**0.7074**	0.0804	1
Depth of Cut	**0.7074**	0.6376	0.6270	0.0804	1
Spindle Speed	0.6469	0.6552	**0.6698**	0.0229	3
	0.6573				

Total Mean Value of GRA 0.5745

Table 23. Main Effects on Mean GRG for Mineral Oil Emulsion Cutting Fluid

Parameter	Level 1	Level 2	Level 3	Max-Min	Rank

Feed rate	**0.6031**	0.5314	0.5520	0.0511	3
Depth of Cut	0.5520	0.5314	**0.6031**	0.0717	2
Spindle Speed	0.5518	0.5018	**0.6329**	0.1311	1
	0.5621				
Total Mean Value of GRA		0.5745			

Table 24. Main Effects on Mean GRG for African Star Oil

Parameter	Level 1	Level 2	Level 3	Max-Min	Rank
Feed rate	**0.6442**	0.5286	0.5342	0.1156	2
Depth of Cut	0.5342	0.5286	**0.6442**	0.1156	2
Spindle Speed	0.3906	0.5005	**0.8160**	0.4254	1
	0.5690				
Total Mean Value of GRA		0.5745			

3.4 Multiple Regression Analysis

Multiple regression analysis (MRA) enables researchers to analyze the strength of the interaction between a result (the dependent variable) and several regression coefficients, as well as the significance of each predictor to the interaction, frequently with the influence of other predictors statistically eliminated. The MRA was used in this study to investigate the effects of the three decision-making strategy factors [31-33]. Cutting temperature and surface roughness were predicted using MINITAB statistical software's regression model to produce mathematical equations for cutting parameters. A multiple regression model was established using the variables such as spindle speed, feed rate, and depth of cut (doc) with a confidence level of 95 percent for cutting temperature (CT) and surface roughness. The R^2 determination coefficients were used to calculate the model's suitability index. The R^2 value increases as it approaches 1 and increases with the model's significance.

3.4.1 Regression Analyses for Cutting Temperature and Surface Roughness (Dry Machining)

$$CT(°C) = 35.82 - 0.00111 speed - 17.6 feed + 0.000001 speed * speed - 13 feed * feed + 0.0510 speed * feed \quad (10)$$

$S = 0.725015 \qquad R^2 = 98.42\%$

$$CT(°C) = 22.3 + 0.0037 speed + 15.9 doc + 0.000001 speed * speed - 5.53 doc * doc + 0.00190 speed * doc \quad (11)$$

$S = 1.84662 \qquad R^2 = 89.75\%$

$$CT(°C) = 45.7 - 128.0 feed + 2.0 doc - 13.0 feed * feed - 5.5 doc * doc + 104.0 feed * doc \quad (12)$$

$S = 4.42158 \qquad R^2 = 41.21\%$

$$SR(\mu m) = -6.27 + 0.00632 speed + 61.2 feed - 0.000001 speed * speed - 145.0 feed * feed - 0.0201 speed * feed \quad (13)$$

$S = 1.06890 \qquad R^2 = 59.74\%$

$$SR(\mu m) = 9.31 + 0.00280 speed - 14.44 doc - 0.000001 speed * speed + 4.87 doc * doc + 0.00033 speed * doc \quad (14)$$

$S = 0.674565 \qquad R^2 = 83.97\%$

$$SR(\mu m) = 16.56 - 14.3\,feed - 19.89doc - 145.0\,feed * feed + 4.87doc * doc + 38.3\,feed * doc \tag{15}$$

$S = 0.657618$ $\quad R^2 = 84.76\%$

3.4.2 Regression Analyses for Cutting Temperature and Surface Roughness (Mineral Oil)

$$CT(°C) = 20.81 + 0.01158speed + 119.6\,feed - 0.000002speed * speed - 333.0\,feed * feed - 0.0316speed * feed \tag{16}$$

$S = 0.676263$ $\quad R^2 = 94.09\%$

$$CT(°C) = 31.25 + 0.00542speed + 1.4doc - 0.000002speed * speed - 1.13doc * doc + 0.00095speed * doc \tag{17}$$

$S = 1.17069$ $\quad R^2 = 82.27\%$

$$CT(°C) = 41.7 + 4.0\,feed - 6.4doc - 333.0\,feed * feed - 1.13doc * doc + 58.0\,feed * doc \tag{18}$$

$S = 1.85243$ $\quad R^2 = 55.62\%$

$$SR(\mu m) = -0.41 + 0.00070speed + 7.1\,feed + 0.000000speed * speed - 16.0\,feed * feed - 0.00226speed * feed \tag{19}$$

$S = 0.227806$ $\quad R^2 = 62.97\%$

$$SR(\mu m) = 2.314 + 0.000430speed - 3.082doc + 0.000000speed * speed + 1.068doc * doc - 0.000047speed * doc \tag{20}$$

$S = 0.0813675$ $\quad R^2 = 95.28\%$

$$SR(\mu m) = 4.05 - 6.3\,feed - 4.26doc - 16.0\,feed * feed + 1.068doc * doc + 7.58\,feed * doc \tag{21}$$

$S = 0.200110$ $\quad R^2 = 71.43\%$

3.4.3 Regression Analyses for Cutting Temperature and Surface Roughness (African Seed Oil)

$$CT(°C) = 25.09 + 0.00425speed + 25.4\,feed - 0.000001speed * speed - 40\,feed * feed - 0.0037speed * feed \tag{22}$$

$S = 0.509660$ $\quad R^2 = 90.47\%$

$$CT(°C) = 26.12 + 0.00150speed + 4.43doc - 0.000001speed * speed - 2.00doc * doc + 0.00146speed * doc \tag{23}$$

$S = 0.634586$ $\quad R^2 = 85.23\%$

$$CT(°C) = 32.56 - 33.5\,feed + 0.18doc - 40\,feed * feed - 2.00doc * doc + 37.0\,feed * doc \tag{24}$$

$S = 0.936453$ $\quad R^2 = 67.84\%$

$$SR(\mu m) = -0.33 + 0.00054speed + 3.8\,feed + 0.000000speed * speed - 8.3\,feed * feed - 0.00165speed * feed \tag{25}$$

$S = 0.265721$ $\quad R^2 = 51.21\%$

$$SR(\mu m) = 1.825 + 0.000549SS - 2.938doc + 0.000000speed * speed + 1.085doc * doc - 0.000173speed * doc \tag{26}$$

$S = 0.0942906$ $\quad R^2 = 93.86\%$

$$SR(\mu m) = 4.00 - 9.6\,feed - 4.28doc - 8.3\,feed * feed + 1.085doc * doc + 7.91\,feed * doc \tag{27}$$

$S = 0.173531$ $\quad R^2 = 79.19\%$

In the case of dry machining, regression analysis for cutting temperature (spindle speed vs. feed rate) was discovered. The cutting temperature second-order polynomial regression value is given in Eq (10). In this instance, the R^2 value is determined to be 98.42% with an S value of 0.725015. The spindle speed and feed rate have a significant impact on the cutting temperature, as shown by the R^2 value. The equation has a good variation in the output response for the specified input process parameters and fits the statistical model appropriately. Eq. 11 outlines the relationship between cutting temperature, spindle speed, and depth of cut. For turning AA6061 using the spindle speed and depth of cut as the input parameters, the R^2 value of 89.75% indicates a less significant impact. Additionally, by considering the impact of feed rate and depth of cut, the second-order polynomial regression equation to determine the cutting temperature is shown in Eq. 12. The generated statistical model's randomness is reflected in the R^2 value. This R^2 value is around 41.21%, indicating that the equation does not statistically fit with the levels of the feed rate and depth of cut that are being considered. Eqs. 13–15 present regression analyses for surface roughness. For the relationships between spindle speed and feed rate, spindle speed and depth of cut, and feed rate and depth of cut, respectively, the model produced R^2 values of 59.74%, 83.97%, and 84.76%. The results showed that surface roughness has a moderate effect on feed rate and depth of cut vs. spindle speed.

Eqs. 16–21 present the regression analyses for the two mineral oil process parameters. Between 95.28% and 55.62% is the R^2 range. The cutting parameters have a significant impact on both surface roughness and cutting temperature, as shown by Eqs. 16, 17, and 20. The equation has a reasonable variation in the output response for the specified input process parameters and fits the statistical model appropriately. The cutting temperature has a moderate effect on the feed rate and depth of cut, according to the R^2 value of 0.7143 in Eq. 21. R^2 is a correlation coefficient that belongs to any multiple regression analysis and should fall between 0.8 and 1.0 [34-35]. In Eqs. 22–27, the African star oil models are displayed. The majority of the values show a strong correlation between the cutting parameters that affect the surface roughness and cutting temperature.

4 Conclusions

The physicochemical properties of indigenous Nigerian non-edible seed oils of African star oil were investigated. ASTM techniques were used to determine various oil characteristics of the bio-lubricants. The cutting fluids were mechanically tested by evaluating characteristics such as surface roughness and cutting temperature during turning operations of Aluminum A6061 alloy. The effect of turning parameters (such as spindle speed, feed rate, and depth of cut) on surface roughness and cutting temperature was also investigated using Taguchi-grey relational analysis. The study can be concluded as follows:

1. African star oil outsmarted mineral oil and dry machining in all machining trials that were conducted.
2. For dry machining with GRG, 0.6698 spindle speed, 0.7074 mm/rev feed, and 0.7074 mm depth of cut are excellent cutting parameters. For mineral oil-based cutting fluid, 0.6329 spindle speed, 0.6031 mm/rev feed, and 0.6031 mm depth of cut are the perfect values. Additionally, 0.6329 spindle speed, 0.6031 mm/rev feed, and 0.6031 mm depth of cut are the optimum values for African star oil-based cutting fluid.
3. The results of the regression analysis demonstrated the validity of the experimental observations. Cutting temperature and surface roughness regression models were at

acceptable levels. The outcomes of this experiment unmistakably demonstrated that African star oil-based cutting fluid is a superior substitute.

4. The sequence of effective machining environments is African star oil, Mineral oil, and dry machining.

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