Advances in Industrial and Manufacturing Engineering 6 (2023) 100115

Contents lists available at ScienceDirect

Advances in Industrial and Manufacturing Engineering

journal homepage: www.sciencedirect.com/journal/advances-in-industrial-and-manufacturing-engineering

Evaluation of palm kernel oil as cutting lubricant in turning AISI 1039 steel using Taguchi-grey relational analysis optimization technique

E.S. Alaba [a,*], R.A. Kazeem [a,b], A.S. Adebayo [a], M.O. Petinrin [a], O.M. Ikumapayi [c,d], T.-C. Jen [b], E.T. Akinlabi [e]

[a] *Department of Mechanical Engineering, Faculty of Technology, University of Ibadan, Ibadan, 200005, Nigeria*
[b] *Department of Mechanical Engineering Science, University of Johannesburg, Auckland Park, Johannesburg, 2006, South Africa*
[c] *Department of Mechanical and Mechatronics Engineering, Afe Babalola University, Ado Ekiti, 360101, Nigeria*
[d] *Department of Mechanical and Industrial Engineering Technology, University of Johannesburg, DFC, 2092, South Africa*
[e] *Department of Mechanical and Construction Engineering, Faculty of Engineering and Environment, Northumbria University, Newcastle, NE7 7XA, United Kingdom*

ARTICLE INFO

Keywords:
Palm kernel oil
Mineral oil
Cutting fluid
Lubricants
AISI 1039 steel

ABSTRACT

Cutting fluids have a known negative impact on productivity, human health, and the environment in the manufacturing sector. A suitable method for reducing the effect of cutting fluids on human health and the environment is minimum quantity lubrication (MQL). In this experiment, AISI 1039 steel was machined using vegetable oil lubricant and MQL. A chemical method was used to extract vegetable oil from palm kernel seeds. Then, using established techniques, the physicochemical and lubricity properties of palm kernel oil (PKO) were ascertained. The Taguchi L_9 (3^3) orthogonal array served as the basis for the planning of the experimental design. Process parameters such as surface roughness, chip thickness ratio, cutting temperature, and material removal rate were measured during the turning operations. The multi-response outputs from TGRA were considered to simultaneously optimize the cutting parameters namely depth of cut, feed rate, and spindle speed. At a temperature of 55°C, 180 min, and particle sizes of 0.2–0.5 mm, an oil yield of 55% by weight was obtained. The viscosity at 40°C, specific gravity, pour, fire, cloud, and flash points of the raw PKO were 117.6 mm^2/s, 0.8940 mg/ml, 21°C, 231°C, 22.3 °*C* and 227°C, respectively. The surface roughness and cutting temperature of PKO improved by 44% and 12%, respectively, when compared with mineral oil. The findings of this research confirmed the effectiveness of the integrated Taguchi-grey relational analysis (TGRA) optimization method and established an experimental foundation for the use of PKO minimum quantity lubrication turning.

1. Introduction

During metal-cutting processes, friction results in the generation of heat at the tool-chip contact. Dimensional accuracy, surface finish, tool life, and machining cost are all impacted by the heat that is produced during the machining process (Çakīr et al., 2007). To lessen this heat, various methods have been used. In the early days, water was used as a cooling medium to lessen the heat, but this leads to issues like the degradation of materials due to corrosion (Sharma et al., 2009; Debnath et al., 2014). Different lubrication and cooling techniques have emerged because of technological advancement. For lubrication and cooling purposes, wet cooling has been the most widely used in industrial applications. In these methods, cutting fluid is recirculated at a flow rate of up to 4–10 L/min (Faga et al., 2017). Given the numerous metal-cutting operations, there are various cutting fluids and cooling strategies. Cutting fluids serves as a coolant to potentially lubricate and reduce the temperature at the tool chip interface. Cutting fluids help to facilitate chip flushing in addition to enhancing machining performance (Kazeem et al., 2022a). Additionally, it lessens the impact of cutting forces. For hundreds of years, water has been used as a cooling agent to help with different metalworking processes. The cutting speed was raised by 30–40% when an excessive flood of water was applied in the cutting area (Sharma et al., 2016). Even though water has a superior temperature efficiency and is readily available, using it as a coolant has the disadvantages of corroding parts and machinery, and providing poor lubrication. Mineral oils were then manufactured as a substitute for water because of their superior lubricating qualities, but their poor cooling capacity and high cost limited their utilization to low-cutting speed operations (Benedicto et al., 2017). Subsequently, as soluble oil was

* Corresponding author.
E-mail address: ezesun4mech@gmail.com (E.S. Alaba).

https://doi.org/10.1016/j.aime.2023.100115
Received 26 July 2022; Received in revised form 28 January 2023; Accepted 8 February 2023
Available online 9 February 2023

Nomenclatures

AISI	American Iron and Steel Institute
ANOVA	Analysis of Variance
AOAC	Association of Official Analytical Chemists
ASTM	American Society for Testing and Materials
GRA	Grey Relational Analysis
GRG	Grey Relational Grade
MQL	Minimum Quantity Lubrication
MRR	Material Removal Rate
pH	Power of Hydrogen
PKO	Palm Kernel Oil
SAE	Society of Automobile Engineers
TGRA	Taguchi Grey Relational Analysis
EL	Electrostatic Lubrication
EMQL	Electrostatic Minimum Quantity Lubrication
HNEMQL	Hybrid Nanoparticles Immersed EMQL
CRC	Chip Reduction Coefficient
LCO_2	Liquid Carbon dioxide
PHSS	Precipitation Hardened Stainless Steel

developed, machining efficiency was enhanced. Soluble oil is applied in machining operations using the flood cooling technique. The reduction of heat for better machining performance was initially given preference over the cost, disposal, flow rate, and environmental effects of cutting fluid (Irani et al., 2005; Gupta et al., 2020). However, due to increased flow rates of mineral oil-cutting fluid, flood lubrication is now considered questionable owing to its detrimental consequences on human health, the environment, and groundwater (Kazeem et al., 2020). The high flow rate of petroleum-based cutting fluids causes environmental deterioration, including water and soil pollution, health implications, and most importantly cutting fluid waste disposal (Kuram et al., 2013). This causes serious concern and has prompted scientists and tribologists to focus more on this field of study.

Vegetable-based oils are gaining popularity as a substitute for mineral-based oils. Vegetable oils offer substantial environmental advantages, renewability, and biodegradability in addition to having exceptional lubricating characteristics that produce excellent results in machining processes (Salih and Salimon, 2021). Vegetable oils mostly consist of triacyl glycerides (also called triglycerides), which are glycerol molecules with three long-chain fatty acids linked at the hydroxyl groups through ester bonds. Vegetable oil triglycerides contain fatty acids that range in length from 14 to 22 carbons (Fox and Stachowiak, 2007; Nitbani et al., 2020). But the degrees of unsaturation differ. Vegetable oils' triglyceride structure gives them advantageous lubricant characteristics. Long, polar fatty acid chains provide efficient lubricant coatings that securely adhere to metallic surfaces and reduce wear and friction (Kazeem et al., 2022a). The increased flash characteristics of vegetable oils reduce the likelihood of smoke and fire development. If a cutting fluid has a higher flash point value, it can be used in high-temperature environments (Shokoohi et al., 2015; Kazeem et al., 2022b). Another characteristic of oil that has a significant impact on machining productivity is viscosity. As the machining temperature rises, vegetable oils' high natural viscosity becomes more apparent. Vegetable oils lose viscosity less quickly than mineral oils do. Vegetable oils are more pliable than mineral oils as the temperature decreases, allowing for quicker dewatering from workpieces and chips. Vegetable oils' higher viscosity index guarantees that they will provide more consistent lubricity over a broad range of temperatures (Wang et al., 2020). Because it has a higher boiling point and a larger molecular structure than other oils, vegetable oil loses less to vaporization and misting.

In the past, bio-based oils were widely used in a variety of products, including hydraulic oil, metalworking fluids, biofuel, and grease. For lubricant applications, numerous studies on the machining characteristics of vegetable-oil-based cutting fluids have been investigated. Belluco and De Chiffre (Belluco and De Chiffre, 2004) investigated the efficacy of vegetable-based lubricants for drilling the AISI 316 L bar with conventional HSS-Co tools. Using five vegetable oils (rapeseed oil with different additive concentrations) as cutting fluids and commercial mineral-based oil as the reference standard oil. Through measurements of cutting forces, chip formation, and tool life, the six cutting oils were evaluated. They concluded that industrial mineral oil performed worse than any vegetable-based fluid. With the best fluid, there were roughly comparable increases in tool life of 177%, while the cutting thrust was reduced by less than 7%. The machining influences of aloe vera oil in the MQL turning of M2 steel were assessed by Agrawal and Patil (2018). When compared to a conventional cutting fluid, aloe vera oil reduced tool wear and surface roughness by 0.14% and 6.7%, respectively. The effectiveness of MQL synthetic ester (MQLSE) and MQL palm oil (MQLPO) during titanium alloy drilling was investigated by Rahim and Sasahara (2011). The tool wear rate in the MQLPO condition was lower than that in the MQLSE condition. Ojolo and Ohunakin (2011) investigated the effects of depth of cut, rake angles, feed rate, and cutting speed on the primary cutting force during the turning of aluminum rod, brass, and mild steel utilizing PKO as the cutting fluid and HSS cutting tool. According to testing results, PKO was used to cut all materials under different cutting circumstances because it reduced the coefficients of friction. Li et al. (2016), looked into the cutting efficiency of different vegetable oils in high-temperature nickel-base alloy MQL grinding, including palm, peanut, sunflower, castor, corn, and soybean oil. The authors concluded that palm oil was the best base oil among the seven vegetable oils because it had the minimum grinding temperature, minimum grinding force, and minimum energy ratio coefficient. They claimed that higher-viscosity vegetable oils have greater lubricating effects and can significantly decrease grinding force. Additionally, Ojolo et al. (2008) looked at how certain vegetable oils affected cutting force while using tungsten carbide tools to convert three distinct materials (aluminum, copper, and mild steel). Shea butter oil, groundnut oil, coconut oil, and PKO were among the oils. The results show that bio-oils might be used as cutting fluids, although their impacts on cutting force depended on the material. Khan et al. (2009) evaluated the effects of MQL utilizing vegetable oil during the turning efficiency of AISI 9310 in terms of cutting temperature, chip formation mode, tool wear, and surface roughness using an uncoated carbide tool. They compared this to wet and dry machining. MQL with vegetable oil appeared to reduce surface roughness. Castor oil usage in grinding operations was explored by Alves and de Oliveira (Alves and Oliveira, 2008), who found that it reduced wheel wear, grinding forces, and surface roughness. Gunerkar and Kuppan (2013) tested two different vegetable cutting oils made of refined sunflower and rapeseed oils together with standard mineral oil to determine the least surface roughness, cutting forces, and tool wear while turning SS316. Vegetable oils are combined with water in a 100:1 water-to-oil ratio. When all factors relating to yield were considered, vegetable oils performed better than mineral oil.

Cryogenic machining and MQL with vegetable oils are emerging as environmentally friendly cutting fluid strategies due to the use of no-cutting oil and very little oil, respectively. Recently, electrostatic minimum quantity lubrication (EMQL) machining has advanced to provide effective lubrication at the tool-chip interface. It combines MQL and electrostatic spraying, two different technologies. A high-voltage electrostatic field is used in the vapor atomization technique known as electrostatic spraying to produce focused droplets with small diameters. Khanna et al. (2022) used a TiAlN-coated carbide tool and a unique approach of sustainable cooling methods, liquid carbon dioxide (LCO_2), MQL, and EMQL, to turn Inconel 718 with the aid of ultrasound. These cooling methods, combined with any two of the aforementioned cooling methods, were used in six different experimental sets. Surface quality, tool wear, chip morphology, power consumption, and specific cutting energy are some of the machining performances that were examined.

The findings demonstrated that using EMQL with canola oil on the flank face and LCO_2 on the rake face significantly reduced power consumption, tool wear, and specific energy without compromising surface quality. Shokrani et al. (2019) compared MQL, flood, and cryogenic cooling to a hybrid cryogenic MQL technique used during end milling Ti–6Al4V with coated solid carbide tools. Tool life, surface roughness, and tool wear were all widely researched. When compared to flood machining, the proposed hybrid cryogenic MQL system resulted in a 30 times longer tool life. Shah et al. (2020) built and tested hybrid nanoparticles immersed EMQL (HNEMQL), EMQL, and electrostatic lubrication (EL) systems to examine how they influenced 15–5 precipitation hardened stainless steel (PHSS). Power consumption, cutting forces, surface roughness, and chip reduction coefficient (CRC) were all measured during their research. For turning 15–5 PHSS, HNEMQL has 2.25%, 4.88%, and 10.75% lower power consumption values than EMQL, EL, and dry respectively. When compared to other cutting fluid strategies, the EL and HNEMQL techniques produce better chip reduction coefficient and surface roughness results.

Several researchers evaluate the effect of machining settings on cutting characteristics using the Taguchi design of experiment (Kazeem et al., 2022c). To cut down on the number of trials, an orthogonal array is randomly chosen for the procedure, and it is chosen depending on the degrees of freedom. The primary function, interaction effects, and a collection of an evaluation function known as the signal-to-noise ratio are all specified in a streamlined sequence using the Taguchi method. Majak et al. (2020), employed AISI 304 stainless steel as the processing material in an evaluation to measure surface roughness and chip compression ratio in MQL turning using three types of vegetable oils, particularly sunflower, coconut, and palm oils. The study and testing using the Taguchi technique with an L_9 (3^4) orthogonal array. When it comes to improving surface roughness and lowering the chip compression ratio, sunflower oil fared better than the other cutting oils. To compare a soybean-based cutting fluid to mineral oil and dry cutting when turning E52100 chromium-alloy steel, Zhang et al. (2012) employed an L_9 (3^4) Taguchi structure. The investigation showed that soy-based oil beat mineral oil in terms of tool wear, and both cutting fluids were consistently efficient at lowering surface roughness. To ascertain the impact of cutting fluids on tool wear surface roughness during AISI 304 austenitic stainless-steel turning, Xavior and Adithan (2009) carried out an exploratory investigation. The orthogonal Taguchi L_{27} (3^4) array was used. With a contribution of 61.54%, feed rate had a significantly larger impact on surface roughness, while cutting speed had a significance of 46.49% on tool wear. Saikiran and Kumar (2019) evaluated the feasibility of cotton seed and groundnut oils during the turning of copper alloys. The ideal process parameters were found to be feed rate (0.0916 mm/rev), spindle speed (835 rpm), depth of cut (1.5 mm), cutting speed (80.89 m/min), and groundnut oil. These parameters helped to achieve better process parameters, such as minimal surface roughness and cutting forces, as well as maximum metal removal rate. Cotton seed oil, PKO, and traditional cutting fluid were evaluated by Lawal et al. (2014) for their ability to reduce cutting forces and surface roughness during AISI 4340 steel turning. ANOVA was used to evaluate how the cutting variables and cutting fluid affected the cutting forces and surface roughness. Palm kernel and cottonseed oils performed significantly better than mineral oils, based on their findings. When milling austenitic stainless steel, AISI 304, Kuram et al. (2010) evaluated the best conditions for tool wear and pressures utilizing processed canola and sunflower oils as well as commercial semi-synthetic oil. The orthogonal array Taguchi L_9 (3^4) was employed in the study. To analyze the major factors that affected the parameters, ANOVA and signal-to-noise ratio analysis were performed. The degradation of the tool and force components was more strongly influenced by the depth of cut.

To model the processing parameters before the actual machining, optimization and response prediction are crucial in the manufacturing industry because products must be produced in large quantities with shorter lead times. To establish the mathematical model and optimize the interactions, the Taguchi design and grey relational approach are frequently used. To determine the most efficient machining factors and their levels, it is essential to investigate the effects of machining factors on their responses. This study used indexable ceramic insert tools to convert AISI 1039 steel, and the TGRA was conducted. Based on feed, cutting speed, and cut depth, it may be used to forecast and optimize cutting temperature, surface roughness, and chip formation. Research studies have used grey relational analysis to optimize process variables with multi-response through grey relational grade. It is common practice to combine all of the cutting parameters that are taken into consideration into a single result that can be employed as the sole characteristic in optimization techniques. The study discovered that AISI 1039 steel machining characteristics had not been adequately investigated. As a result, an effort is made to determine this workpiece's machinability using TGRA.

2. Materials and methods

2.1. Extraction and characterization of PKO

Palm kernel seed samples were considered in this research, and it was purchased from a local market in Ibadan, Nigeria. Palm kernel seeds were sun-dried at an average temperature of 25 °C for one week before the milling. Milled palm kernel seeds range between 0.2 and 0.5 mm in particle size. Using n-hexane, oil extraction was carried out at a temperature of 55 °C. The extraction process took 180 min at a temperature of 55 °C with particles that ranged in size from 0.2 to 0.5 mm. PKO was studied using crude oil extracts to determine its physical and thermal properties (Kazeem et al., 2020). This was carried out to determine feasible conditions of the oils as cutting fluid. Various tests that were carried out include percentage oil yield, pH, relative density, viscosity at 40 °C, specific gravity, cloud point, pour point, fire point, and flash point. Table 1 shows the determination of the measured properties.

2.2. Cutting conditions and design of experiment

In this experiment, medium carbon steel AISI 1039 solid cylindrical bars measuring 120 mm in length and 40 mm in diameter underwent a turning procedure. This steel was selected as a raw material for its adaptable properties, which include heat resistance, water resistance, high strength at elevated temperatures, and excellent resistance to chloride pitting and crevice corrosion cracking. Strategic applications including maritime engineering, furnaces and gas turbines, chemical

Table 1
Determination of oil properties.

Parameter	Method	Equation	Definition
Specific gravity	ASTM D1217-15	$\frac{W_o}{W_{evw}}$	W_o = weight of oil, W_{evw} = an equal volume of water
Viscosity	ASTM D445	$Adt - \frac{Bd}{t}$	A and B = constants, t = amount of time in seconds; Viscosity expressed in centipoises *(cP)*, d = Density in *g/ml*
Relative density	–	$RD = \frac{\rho_{oil}}{\rho_{water}}$	ρ_{oil} = The density of oil. ρ_{water} = Density of water
Oil yield	AOAC	$OY = \frac{W_{EO}}{W_{SS}} \times 100$	W_{EO} = Weight of extracted oil (g); W_{SS} = Weight of seed sample (g)
Ph	pH Meter		
Cloud point	ASTM D2500		
Pour point	ASTM D97		
Fire point	ASTM 90-92D		
Flash point	ASTM D1310		

processing facilities, boilers and pressure vessels, and nuclear power plants benefit from its advantages. The chemical parameters and physical/mechanical qualities of medium carbon steel AISI 1039 are listed in Tables 2 and 3, respectively. The turning insert employed in this study was indexable ceramic insert tools (insert model: CNMG12040408). The experiment was conducted using a standard metalworking lathe, Colchester 1800 machine. The cutting fluids were spread externally on the cutting interface using an MQL delivery. The cooling of cutting tools and workpieces was carried out by convective heat transfer through the compressed air while the lubrication of the machining interface was done by the oil droplets. The oil was flowing at a rate of 2.3 mL/h and the air pressure was 6 bar. By minimizing lubricant consumption, which may be accomplished by providing an accurate and sufficient supply of lubricant to the machining zone, this system also lowers the cost of lubrication.

This study evaluated the effects of several cutting settings on the cutting temperature, surface roughness, chip thickness, and material removal rate (MRR). Finding the best set of cutting settings also involved using the multi-objective optimization method. To evaluate the effects of the various cutting settings on the cutting temperature, surface roughness, chip thickness, and MRR, orthogonal experiments were made using the Taguchi design technique. Cutting parameters (spindle speed, depth of cut, and feed rate) were seen as the control variables, whilst turning characteristics (cutting temperature, surface roughness, chip thickness, and MRR) were viewed as the reaction characteristics. Table 4 displays the orthogonal experiment's factors and levels. The L_9 (3^3) orthogonal array was chosen to create the experiment using the Taguchi design approach. The evaluation was carried out mechanically with the developed palm kernel oil and the commercial SAE 40 lubricating oil (mineral oil). Hence, each cutting fluid was subjected to nine experimental trials.

2.3. Measuring devices

One of the most significant quality indicators in the machining process is surface quality or roughness. After each experiment in the current investigation, the average values of surface roughness *(Ra)* were measured. Ra measurements were taken using a portable surface-roughness tester, the SRT6200. The measuring device has already been calibrated before surface roughness measurements. A fresh cutting tool was used to machine each surface. Following each experiment, measurements were made on the workpiece. To reduce variance in all tests, surface roughness values were measured at various points on the workpiece. From there, a mean value of surface roughness was determined. Cutting temperature readings were taken using a PeakTech Infrared thermometer and an emissivity value of 0.12 for AISI 1039 steel furnished by Calex Electronics Limited (Kazeem et al., 2020). By directing the thermometer's probe at the chip-tool contact while it was being machined, the level of heat there was determined. The chip-tool interface was held 5 cm apart from the infrared temperature sensor by hand. Three samples of each sample were taken, and the average reading was computed for each sample. Eq. (5) and Eq. (6) are used to calculate the volumetric rate of material removal rate and the chip thickness ratio, respectively.

$$MRR = v \times f \times d\left(mm^3 / \min\right) \tag{5}$$

where $v-$ spindle speed (rev/min), $f-$ feed rate (mm/rev), and $d-$ depth of cut (mm)

Table 3
Mechanical and physical characteristics of AISI 1039 steel.

Property	Value	Unit
Yield strength	502.45	MPa
Tensile strength	595.62	MPa
Hardness	160–180	HRC
Modulus	152.66	GPa

Table 4
Factor and levels of the orthogonal array.

Factor	Level		
	Level 1	Level 2	Level 3
Spindle speed (rpm)	410	555	745
Feed rate (mm/rev)	0.10	0.20	0.25
Depth of cut (mm)	0.75	1.00	1.25

$$r = \frac{t}{t_c} (\mu m) \tag{6}$$

where $t-$ uncut chip thickness and t_c- cut chip thickness

2.4. Grey relational analysis

When just a portion of the information is known and the rest is unclear, the system is said to be "grey" (Jozić et al., 2015). Grey systems will always offer a range of viable solutions since ambiguity is a given. Based on this finding, grey relational analysis (GRA) may be successfully used to address the complex relationships between the specified performance criteria. The grey relational grade (GRG) is defined favorably as an indication of numerous performance qualities for assessment in this study. The 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 an optimization of a single response GRG. The method for obtaining the grey relationship grade is detailed more below.

2.4.1. Pre-processing

To change the original sequence into a comparable sequence, data pre-processing is performed. The obtained numerical data is uniformly distributed between 0 and 1. Following the characteristics of the data stream, many data pre-processing techniques exist. In this study's smaller-the-better performance characteristics, surface roughness, cutting temperature, and chip thickness, the modified value of the original sequence may be expressed as provided in Eq. (7):

$$U_{ij} = \frac{\max\left(k_{ij}\right) - k_{ij}}{\max\left(k_{ij}\right) - \min\left(k_{ij}\right)} \tag{7}$$

The normalized value of the initial sequence for the performance characteristic of greater-the-better material removal rate may be expressed as indicated in Eq. (8):

$$U_{ij} = \frac{k_{ij} - \min\left(k_{ij}\right)}{\max\left(k_{ij}\right) - \min\left(k_{ij}\right)} \tag{8}$$

where k_{ij} are the original data

The grey relational coefficient is then applied to determine how near x_{ij} is to x_{oj}. The greater the grey relationship coefficient, the closer u_{ij} and

Table 2
Chemical characteristics of AISI 1039 steel.

Element	C	Si	Mn	P	S	Cr	Ni	Al	Zn	Fe
Weight Percentage	0.39	0.281	0.837	0.022	0.019	0.138	0.007	0.034	0.002	89.2

u_{oj} are to each other. The grey relationship coefficient may be calculated as follows:

$$\gamma(U_{oj}, U_{ij}) = \frac{(\Delta_{\min} + \xi\, \Delta_{\max})}{(\Delta_{ij} + \xi\, \Delta_{\max})} for\ i = 1, 2, .., m\ and\ j = 1, 2, \ldots\ldots, n \quad (9)$$

where $k(u_{oj}, u_{ij})$ is the grey relational coefficient between u_{oj} and u_{ij}

$$\Delta_{\min} = \min\{\Delta_{ij}, i = 1, 2, \ldots\ldots, m \text{ and } j = 1, 2, \ldots\ldots, m\}$$

$$\Delta_{\max} = \max\{\Delta_{ij}, i = 1, 2, \ldots\ldots m \text{ and } j = 1, 2, \ldots\ldots n\}$$

ξ as a distinguishing coefficient, $\xi \in (0, 1)$

The GRG is the measuring procedure for measurement in grey relational space. A GRG is a weight matrix of the grey relational coefficients derived using Eq. (10):

$$\Gamma(u_o, u_i) = \sum_{j=1}^{n} V_j \gamma(U_{oj}, U_{ij}) \text{ for } i = 1, 2, \ldots m \quad (10)$$

$$where \quad \sum_{j=1}^{n} V_j = 1$$

$\Gamma(u_o, u_i)$ is the GRG between the comparability sequence, u_i and the reference sequence u_o

The GRG demonstrates how the comparative and reference sequences are comparable. When contrasted to the reference sequence, the trial with the highest GRG implies that the comparability sequence is most likely the most comparable, making it the best decision.

2.4.2. Determination of ANOVA

ANOVA is a method of segmenting variables in an experiment into distinct sources of uncertainty and the corresponding sense of independence. It is employed in this study to determine which adjustable variable has the greatest influence on the performance characteristic. This is done by separating the contributions from each controllable parameter and the error in the overall variability of the GRG (measured as the sum of the squared deviations from the total mean of the GRG).

3. Results and discussion

3.1. Physiochemical and lubricity properties of PKO

The physical, chemical, and lubricity properties of the oil extracts from PKO are shown in Table 5. The extracted PKO was deep yellow, and the condition of the oil extracts was generally liquid at room temperature. The oil content in palm kernel was determined to be 55% by weight. The oil yield was moderately high and can be compared with those obtainable in the literature. Hassan et al. (2000), recorded a 50% oil yield for PKO. Other oil yields reported include 49.82% by Egbuna et al. (2021), 51.35% by Yerima et al. (2018), and 47% by Zaidul et al. (2007). The oil production found in this study might be related to genetic variances, climate, plant species, soil conditions, and inappropriate processing methods including exposing harvested seeds to sunlight for an extended period, which has the potential to significantly reduce oil yield. Oil yield from palm kernel can be considered economical for the commercial production of cutting fluids in Nigeria. The specific gravity of the oil extract ranges from 894.0 to 925.6 kgm^{-3} when measured thrice. The average specific gravity recorded was 906.5 kgm^{-3}. This is in close agreement with the specific gravity value of 0.910 g/ml reported by Egbuna et al. (2021). The pH of the oil extracts ranges from 5.8 to 6.9 when measured thrice (average pH of 6.8). The viscosity of a cutting fluid is very vital in determining the performance of the cutting fluid because the lower the viscosity the better the cutting fluid since viscosity determines the internal friction of a fluid. The viscosity of PKO at 40°C viscosity was obtained to be 117.6 mm^2/s. This is a bit higher than the viscosity of SAE 40 lubricant with 105.1 mm^2/s. The ability of the samples to combine with other liquids and the compatibility of PKO with either heavy or light-load engines were assessed by the density of the oil. The ability of the samples to mix with other liquids and the compatibility of PKO with either heavy-duty engines or light-duty engines were assessed by the density of the oil. According to the findings, PKO, SAE 40, and SAE 30 had respective densities of 0.8940, 0.8567, and 0.8754 mg/ml (https://wiki.anton-paar.com/en/engine-oil/.). According to the findings, PKO has a good specific gravity and will be beneficial in the event of water contamination since the water will sink below the oil and may be drained off.

The lubricity properties of vegetable oils are important to maintain a stable lubricating film at the metal contact zone during machining operations. In this study, lubricity properties such as flash, pour, cloud, fire, and flash points values were obtained and presented in Table 5. Based on the results, it was determined that PKO had a flash point of 227°C and a fire point of 231°C. This characteristic of the lubricant demonstrates how they react to heat and flame under controlled circumstances. In contrast, SAE 40 and SAE 30 have flash values of 260 and 243 °C, respectively. In a similar vein, SAE 40 and SAE 30 were said to have fire points of 300 and 290 °C, respectively (http://lejpt.academicdirect.org/A08/01_08. htm.). The findings make it abundantly evident that PKO has excellent flash and fire points when compared to those of common lubricants like SAE 40 and SAE 30. The sample's pour point for PKO was 21°C, compared to SAE 30's pour point of 9°C and SAE 40's pour point of 21°C, respectively. This indicates that PKO has the same pour point as SAE 30 while having a far lower firing point than SAE 30 and SAE 40. This implies that PKO might be applied to humid as well as temperate locations. The pour point of raw palm kernel, according to Egbuna et al. (2021), was 18 °*C*. The solvent employed for the laboratory extraction may be the cause of the minor discrepancy. Since a liquid, in particular, a lubricant must reach its pour point before it stops flowing, lowering the temperature causes the samples to stop flowing. According to these theories, PKO has a pour point that makes it suitable for use as lubricating oil in machining.

Table 5
Physiochemical and lubricity properties of PKO.

Property	Unit	Result Obtained
Cloud point	°*C*	22.3
Pour point	°*C*	21.0
Flash point	°*C*	227.0
Fire point	°*C*	231.0
Specific gravity	kgm^{-3}	906.5
Colour	–	Deep yellow
Viscosity at 40 °C	mm^2/s	117.6
pH	–	6.8
Oil yield	–	55%
Density	mg/ml	0.8940

3.2. Experimental results for AISI 1039 steel machining with different cutting fluids

The results obtained for chip thickness, material removal rate, surface roughness, and cutting temperature by using two types of cutting fluids namely, PKO and mineral oil lubricants are presented in Tables 6 and 7. For better comparison of the lubricant oils, the data was converted into charts as shown in Figs. 1–3. It can be observed that chip removal rate, material removal rate, cutting temperature, and surface roughness fell within the ranges of 50.01–225.01 μm, 41.0–186.3 mm^3/min, 0.381–1.286 μm and 32.30–76.00 °*C*; and 50.01–150.31 μm, 41.0–186.3 mm^3/min, 0.37–2.96 μm and 37.0–61.00 °*C* for PKO and mineral oils, respectively. In general, chip thickness, material removal rate, surface roughness, and cutting temperature were 1075.22 ± 63.46 μm, 937.6 ± 50.52 mm^3/min, 6.432 ± 0.282 μm and 417.89 ± 13.58 °*C*; and 950.5 ± 34.9 μm, 937.6 ± 50.52 mm^3/min, 11.57 ± 0.76 μm and 474.65 ± 8.23 °*C*; for PKO cutting fluid and mineral oil, respectively. It

Table 6
Experimental results for AISI 1039 steel machining with PKO.

Exp. order	Spindle speed (*rev* /min)	Feed rate (*mm* /*rev*)	Depth of cut (*mm*)	Surface roughness (μm)	Cutting Temp. ($^{\circ}C$)	Chip thickness (μm)	MRR (mm^3 /min)
1	410	0.10	1.00	0.501	35.07	100.01	41.0
2	410	0.20	1.25	0.654	50.23	175.03	102.5
3	410	0.25	0.75	0.475	32.30	150.04	76.9
4	555	0.10	0.75	0.708	42.33	50.01	41.6
5	555	0.20	1.00	0.808	47.20	75.02	111
6	555	0.25	1.25	1.286	32.76	225.01	173.4
7	745	0.10	1.25	0.381	48.67	50.05	93.1
8	745	0.20	0.75	0.629	53.33	75.04	111.8
9	745	0.25	1.00	0.990	76.00	175.01	186.3

Table 7
Experimental results for AISI 1039 steel machining with mineral oil.

Exp. order	Spindle speed (*rev* /min)	Feed rate (*mm* /*rev*)	Depth of cut (*mm*)	Surface roughness (μm)	Cutting Temp. ($^{\circ}C$)	Chip thickness (μm)	MRR (mm^3 /min)
1	410	0.10	1.00	1.31	54.33	150.01	41.0
2	410	0.20	1.25	0.93	50.00	100.04	102.5
3	410	0.25	0.75	1.84	37.00	125.04	76.9
4	555	0.10	0.75	2.96	54.33	75.02	41.6
5	555	0.20	1.00	0.37	57.00	100.01	111
6	555	0.25	1.25	0.79	59.33	125.02	173.4
7	745	0.10	1.25	0.75	61.00	50.01	93.1
8	745	0.20	0.75	1.43	59.33	150.31	111.8
9	745	0.25	1.00	1.19	42.33	75.04	186.3

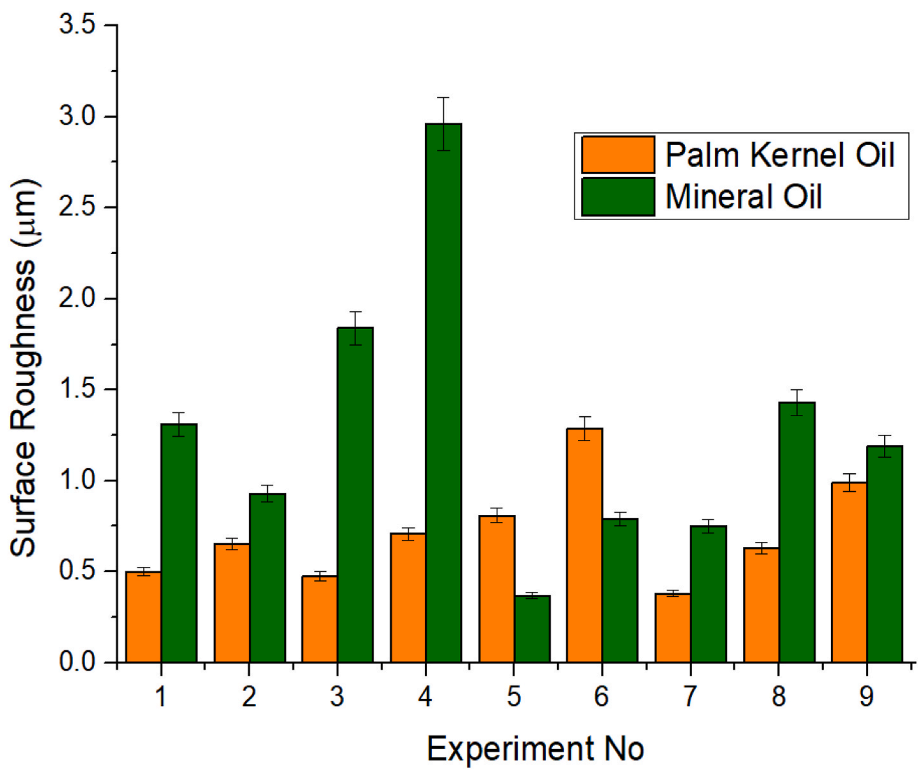

Fig. 1. Effect of minimum quantity lubrication on surface roughness of AISI 1039 steel.

is claimed that better machining is attained with lower chip thickness, surface roughness, and cutting temperature but a higher material removal rate. From the general point of view, PKO cutting fluid performed exceedingly better than mineral oil. PKO cutting fluid outsmarted mineral oil in terms of surface roughness and cutting temperature while they both have equal values of material removal rates. The mineral oil was more effective to reduce the chip thickness during the machining of AISI 1039 steel. Changing values of the actual cutting angle, the development of built-up edges, and variations in fiction are frequently to blame for variations in chip compression. The key factors influencing chip contraction are the cutting angle, spindle speed, feed rate, cutting fluid, the metal being machined, and its mechanical characteristics (Obi et al., 2013).

When mineral oil lubricants were used, the chips generated were thinner. A better lubricant should, in an ideal setting, result in a greater decrease in chip compression with feed and speed, which is a sign of a decrease in cutting force, power consumption, and cutting temperature. In this study, the mineral oil played a good role to reduce the chip

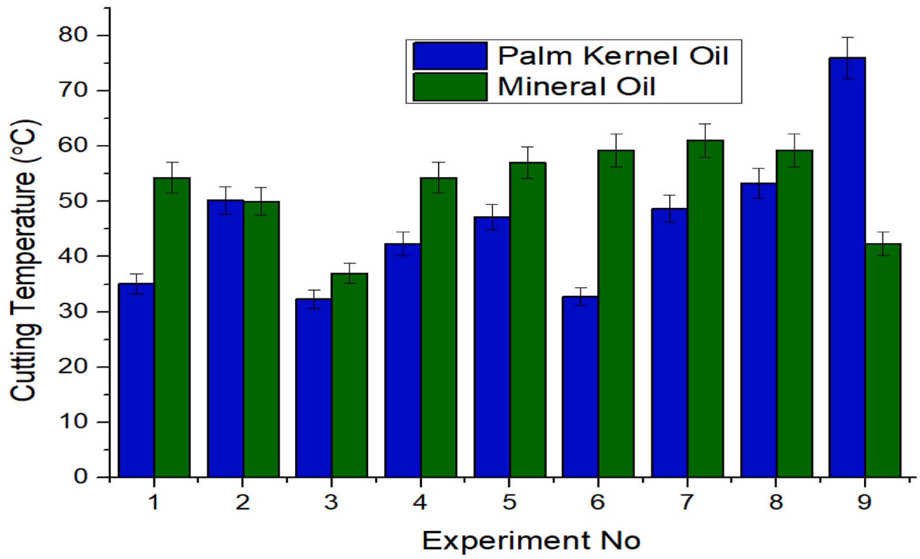

Fig. 2. Effect of minimum quantity lubrication on cutting temperature of AISI 1039 steel.

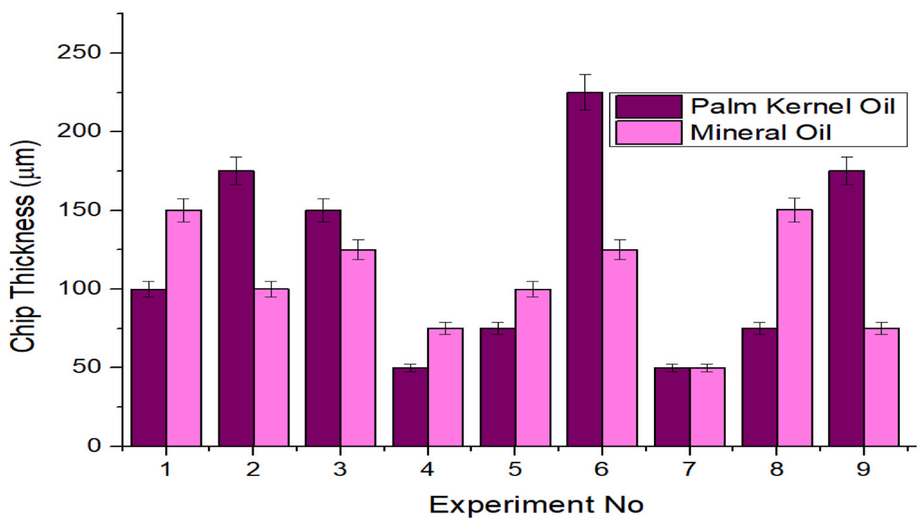

Fig. 3. Effect of minimum quantity lubrication on chip thickness ratio of AISI 1039 steel.

thickness ratio. The palm kernel cutting oil will tend to cause a built-up edge on the workpiece due to its higher chip thickness ratio values. As regards cutting temperature and surface roughness, PKO exhibited an excellent performance than the conventional cutting fluid. Fatty acid characteristics may be used to explain how PKO cutting fluid behaves in terms of surface roughness and cutting temperature. The behavior experienced by PKO is similar to Lawal et al. (2014).

The electrochemical contact between the tool and the workpiece may be responsible for the surface roughness that significantly decreased when PKO lubricants were used. The use of cutting fluid is thought to minimize the coefficient of friction at the tool-workpiece interfaces, leading to a considerable decrease in surface roughness and cutting temperature (Obi et al., 2013). It is thought that between the tool-workpiece contacts, a thin boundary layer developed. PKO was able to generate high-strength lubricant coatings that interact aggressively with the contact surfaces due to its high concentration of saturated fatty acids and viscosity. Vegetable oil triglycerides are well recognized for their exceptional lubricity because of the trigycerol molecule that adheres to the metal surface. This allows the formation of a monolayer film with nonpolar fatty acid chains, which allows sliding at the contact surface. This is in accordance with Ojolo et al. (2008). The study found that as spindle speed and feed rate increased, chip-tool interface temperature increased under both lubrication conditions, owing to an increase in energy input and the roles of cutting parameter variation. This is consistent with Khan et al. (2009). According to the experiment results of the two cutting fluids studied, the surface roughness of PKO was reduced by 44% when compared to mineral oil, and the cutting temperature of PKO was reduced by approximately 12% when compared to mineral oil.

3.3. Evaluation of results with grey relational analysis

For PKO and mineral oil, the impacts of each cutting parameter at various levels are plotted and displayed in Figs. 4 and 5, respectively. Tables 8 and 10 provide the grey relationship generation values and deviation sequence, respectively. The greatest mean GRG values for mineral oil and PKO are used to establish the optimal parametric combination. A stronger connection to the reference sequence and higher quality are both indicated by a GRG with a higher value. Therefore, for multiple responses, a spindle speed of 745 rev/min (level 3), feed rate of 0.1 mm/rev (level 1), and depth of cut of 0.75 mm (level 1) is the optimal specifications for PKO lubricant. A spindle speed of 745 rev per

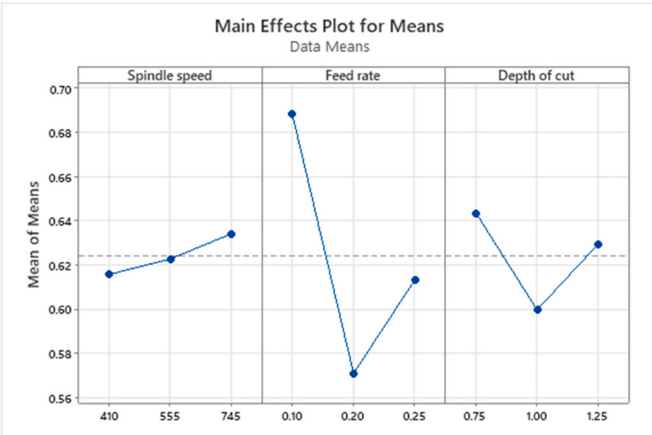

Fig. 4. Main effects plot for GRG (PKO lubricant).

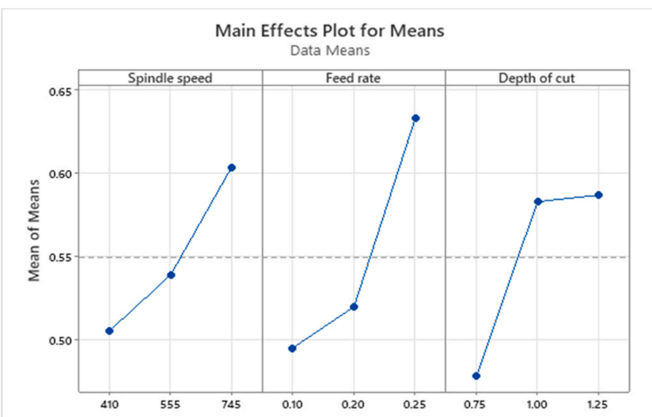

Fig. 5. Main effects plot for GRG (mineral oil lubricant).

minute (level 3), feed rate of 0.25 mm per revolution (level 3), and depth of cut of 1.25 mm (level 3) are the appropriate parameters for mineral oil lubricant. This agrees with Panda et al. (2016). The lowest values of surface roughness, chip thickness ratio, cutting temperature, and highest values of material removal rates are provided by the mean GRG. The grey relational coefficient and grey relational grade for mineral oil and PKO, respectively, are shown in Tables 9 and 11.

The deviation of the mean GRG for the turning parameters was 0.018 rev/min for spindle speed, 0.111 mm/rev for feed rate, and 0.044 mm for depth of cut (see Table 12). This research reveals that, when compared to spindle speed and depth of cut, feed rate has the biggest impact on multi-responses in turning operations using PKO as the lubricant. Feed rate > depth of cut > spindle speed is the order in which process factors have the greatest impact on multiple responses. Table 13 displays the responses for mineral oil lubricant. According to the investigation, feed rate has a greater impact on multiple reactions during turning operations using a mineral oil lubricant than the depth of cut and spindle speed.

3.4. Evaluation of ANOVA

The ANOVA was used to identify the specific interactions of each control element in the outcomes of the experiment. The ANOVA was used to determine the significant machining parameters. ANOVA analysis was carried out using a 5% level of significance and a 95% level of confidence. The control factor importance was shown by the F values. The final column of Tables 14 and 15 displays the percentage contribution of each parameter. The effect rate of the control factors on the outcomes is displayed in this column. The GRG values were found to be affected by spindle speed, feed rate, and depth of cut with respective effects of 1.2%, 51%, and 7.2%, according to the findings of the PKO. In the instance of mineral oil, an ANOVA analysis revealed that the GRG values were impacted by the spindle speed, feed rate, and depth of cut with corresponding effects of 16%, 35.50%, and 24.30%. As a result, the feed rate had the greatest impact on the GRG values for both mineral oil and PKO. Another intriguing conclusion drawn from the ANOVA tables is that while the P-value values are higher than 0.05, the spindle speed, feed rate, and depth of cut have no statistically significant impact on the GRG values at the reliability level of 95%.

Fig. 6 shows the GRG comparison for PKO and mineral oil, and it was observed that the value of GRG for PKO is larger than that of mineral oil in most experimental runs. The main contribution of this work was to successfully demonstrate that vegetable oils can be applied as metalworking fluid in machining processes. The quality of vegetable oil-based cutting fluid was examined by performing physical and chemical analysis, and it proved to be very satisfactory in terms of excellent results of the analyses, as compared to commercial mineral oil (SAE 40 lubricating oil).

Table 9
Grey relational coefficient and grey relational grade for PKO.

Exp No.	Grey Relational Coefficient				Grade	Rank
	R_a	Cutting Temp.	Chip Thickness	MRR		
1	0.790	0.887	0.636	0.333	0.662	3
2	0.624	0.549	0.412	0.464	0.512	9
3	0.828	1.000	0.467	0.399	0.673	2
4	0.581	0.685	1.000	0.334	0.650	4
5	0.514	0.595	0.778	0.491	0.594	7
6	0.333	0.979	0.333	0.849	0.624	5
7	1.000	0.572	1.000	0.438	0.752	1
8	0.646	0.510	0.778	0.494	0.607	6
9	0.426	0.333	0.412	1.000	0.543	8

Table 8
Grey relational generation values and deviation sequence for PKO.

Exp No.	Normalized Value				Deviation Sequence			
	R_a	Cutting Temp.	Chip Thickness	MRR	R_a	Cutting Temp.	Chip Thickness	MRR
1	0.867	0.937	0.714	0.000	0.133	0.063	0.286	1.000
2	0.698	0.590	0.286	0.423	0.302	0.410	0.714	0.577
3	0.896	1.000	0.428	0.247	0.104	0.000	0.572	0.753
4	0.639	0.770	1.000	0.004	0.361	0.230	0.000	0.996
5	0.528	0.659	0.857	0.482	0.472	0.341	0.143	0.518
6	0.000	0.989	0.000	0.911	1.000	0.011	1.000	0.089
7	1.000	0.625	1.000	0.359	0.000	0.375	0.000	0.641
8	0.726	0.519	0.857	0.487	0.274	0.481	0.143	0.513
9	0.327	0.000	0.286	1.000	0.673	1.000	0.714	0.000

Table 10
Grey relational generation values and deviation sequence for mineral oil.

Exp No.	Normalized Value				Deviation Sequence			
	R_a	Cutting Temp.	Chip Thickness	MRR	R_a	Cutting Temp.	Chip Thickness	MRR
1	0.637	0.278	0.003	0.000	0.363	0.722	0.997	1.000
2	0.784	0.458	0.501	0.423	0.216	0.542	0.499	0.577
3	0.432	1.000	0.252	0.247	0.568	0.000	0.748	0.753
4	0.000	0.278	0.751	0.004	1.000	0.722	0.249	0.996
5	1.000	0.167	0.501	0.482	0.000	0.833	0.499	0.518
6	0.838	0.070	0.252	0.911	0.162	0.930	0.748	0.089
7	0.853	0.000	1.000	0.359	0.147	1.000	0.000	0.641
8	0.591	0.070	0.000	0.487	0.409	0.930	1.000	0.513
9	0.683	0.778	0.750	1.000	0.317	0.222	0.250	0.000

Table 11
Grey relational coefficient and grey relational grade for mineral oil.

Exp No.	Grey Relational Coefficient				Grade	Rank
	R_a	Cutting Temp.	Chip Thickness	MRR		
1	0.579	0.409	0.334	0.333	0.414	9
2	0.698	0.480	0.501	0.464	0.536	6
3	0.468	1.000	0.401	0.399	0.567	5
4	0.333	0.409	0.667	0.334	0.436	7
5	1.000	0.375	0.501	0.491	0.592	3
6	0.755	0.350	0.401	0.849	0.589	4
7	0.773	0.333	1.000	0.438	0.636	2
8	0.550	0.350	0.333	0.494	0.432	8
9	0.612	0.692	0.667	1.000	0.743	1

Table 12
Main effects on mean GRG for PKO.

Parameter	Level 1	Level 2	Level 3	Max-Min	Rank
Spindle Speed	0.616	0.617	**0.634**	0.018	3
Feed Rate	**0.683**	0.571	0.613	0.111	1
Depth of Cut	**0.643**	0.600	0.629	0.044	2

Table 13
Main effects on mean GRG for mineral oil.

Parameter	Level 1	Level 2	Level 3	(Max-Min)	Rank
Spindle Speed	0.506	0.539	**0.604**	0.098	3
Feed Rate	0.495	0.520	**0.633**	0.138	1
Depth of Cut	0.478	0.583	**0.587**	0.109	2

Table 14
Results of ANOVA on GRG for PKO lubricant.

Source of Variance	Degree of Freedom	Sum of Squares	Mean of Sum of Squares	F-Value	Percent Contribution
Spindle speed	2	0.000500	0.000250	0.03	1.20
Feed rate	2	0.021042	0.010521	1.26	51.00
Depth of cut	2	0.002984	0.001492	0.18	7.20
Error	2	0.016738	0.008369		40.60
Total	8	0.041264			100.00

3.5. *Mathematical model*

The parameters spindle speed *(v)*, feed *(f)*, and depth of cut were used to develop a multiple regression model with a 95 percent confidence level for both responses, such as surface roughness *(Ra)* and cutting temperature *(T)*. The value of the model's determination coefficients was calculated to assess the model's suitability (R^2). The relevance of the model increases as the R^2 value increases, that is, when it approaches or approaches one. Based on the experimental results, Eqs (11)–(18) present first and second-order mathematical models for surface roughness and cutting temperature, together with their R^2 values for PKO and mineral oil.

Table 15
Results of ANOVA on GRG for mineral oil lubricant.

Source of Variance	Degree of Freedom	Sum of Squares	Mean of Sum of Squares	F-Value	Percent Contribution
Spindle speed	2	0.01490	0.007448	0.63	16.00
Feed Rate	2	0.03233	0.016165	1.36	35.50
Depth of cut	2	0.02278	0.011390	0.96	24.30
Error	2	0.02382	0.011911		24.20
Total	8	0.09383			100.00

First Order Regression Equation for PKO

$$R_a(\mu m) = -0.235 + 0.000279v + 2.45f + 0.339d \tag{11}$$

$$Model\ Summary: R^2 = 41.86\%$$

$$CT(^\circ C) = 1.2 + 0.0620v + 40.5f + 2.5d \tag{12}$$

$$Model\ Summary: R^2 = 48.18\%$$

Second Order Regression Equation for PKO

$$R_a(\mu m) = -0.15 + 0.00524v - 15.95f + 0.59d - 0.000004v^2 + 18.2f^2 - 1.24d^2 + 12.16fd \tag{13}$$

$$Model\ Summary: R^2 = 98.73\%$$

$$CT(^\circ C) = 77.0 - 0.561v - 45f + 229d + 0.000542v^2 - 980f^2 - 152d^2 + 422fd \tag{14}$$

$$Model\ Summary: R^2 = 79.19\%$$

First Order Regression Equation for Mineral Oil

$$R_a(\mu m) = 4.84 - 0.00074\ v - 3.38\ f - 2.507\ d \tag{15}$$

$$Model\ Summary: R^2 = 61.38\%$$

$$CT(^\circ C) = 39.7 + 0.0194\ v - 60.6\ f + 13.1\ d \tag{16}$$

$$Model\ Summary: R^2 = 47.46\%$$

Second Order Regression Equation for Mineral Oil

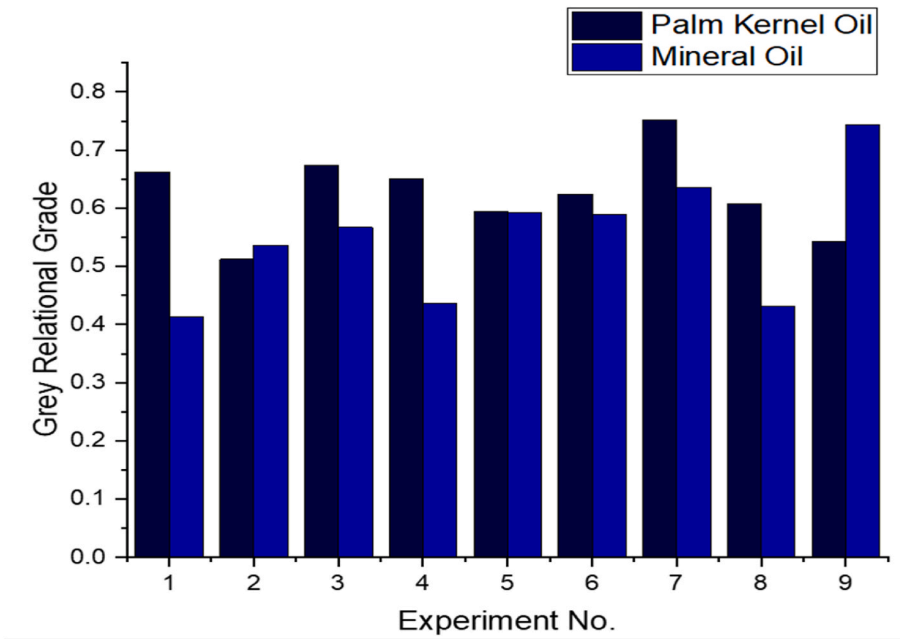

Fig. 6. Grey relational grade comparison of PKO and mineral oil.

$$R_a(\mu m) = 24.2 - 0.0168\ v - 64.9f - 23.3d + 0.000014v^2 + 99.3\,f^2 + 7.89\ d^2 + 27.5\,fd \quad (17)$$

Model Summary : $R^2 = 94.58\%$

$$CT(^\circ C) = -29 + 0.296\ v + 328f - 61d - 0.000238v^2 - 1156f^2 + 36\ d^2 + 7\,fd \quad (18)$$

Model Summary : $R^2 = 77.73\%$

Particularly for surface roughness, which is 41.86% and 48.18% for cutting temperature for PKO and surface roughness of 61.38%, and cutting temperature of 47.46% for mineral oil, the first-order regression model has relatively low determination coefficient values. The second-order model, however, displayed a greater R^2 value that was very near to 1. It is considered to be statistically significant and acceptable, representing the model's best fit, and it demonstrates how closely the projected values match the experimental data. As a consequence, the created second-order model suggests that the experimental and anticipated outcomes have strong relationships. This comparative finding demonstrates that the created second-order model may be securely used to forecast the anticipated outcomes before the experiment in MQL-assisted turning of AISI 1039 steel.

4. Conclusion

The physicochemical and lubricity properties of PKO were investigated. The oil characteristics were determined using standard techniques. The cutting fluids were mechanically tested by measuring surface roughness, cutting temperature, material removal rate, and chip thickness ratio during turning operations of AISI 1039 steel. Using TGRA, the effect of turning parameters (such as spindle speed, feed rate, and depth of cut) on surface roughness, cutting temperature, material removal rate, and chip thickness were also evaluated. The study can be summarized as follows.

1. The surface roughness and cutting temperature of PKO improved by 44% and 12%, respectively, when compared with mineral oil.
2. In general, chip thickness, material removal rate, surface roughness, and cutting temperature were 1075.22 ± 63.46 μm, 937.6 ± 50.52 mm^3/min, 6.432 ± 0.282 μm and 417.89 ± 13.58 $^\circ C$; and 950.5 ± 34.9 μm, 937.6 ± 50.52 mm^3/min, 11.57 ± 0.76 μm and 474.65 ± 8.23 $^\circ C$; for PKO cutting fluid and mineral oil, respectively.
3. A spindle speed of 745 rev/min, feed rate of 0.1 mm/rev, and depth of cut of 0.75 mm are the optimal specifications for PKO lubricant for multiple responses. Mineral oil lubricant requires a spindle speed of 745 rev/min, a feed rate of 0.25 mm per revolution, and a depth of cut of 1.25 mm.
4. Feed rate had the greatest impact on the GRG values for both mineral oil and PKO.

Data availability

The research data has been included in the manuscript

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