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Investigating the use of soluble oil derived from Magarya nuts as a cutting fluid in machining processes

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Abstract

The growing environmental concerns associated with petroleum based cutting fluids have intensified the search for sustainable and biodegradable alternatives in machining operations. This study investigated the suitability of Magarya nut (Diospyros mespiliformis) oil as an alternative cutting fluid for metal machining applications. Magarya nuts were processed, and the extracted oil was characterized for its physicochemical properties, including density, viscosity, pH, flash point, pour point, acid value, saponification value, moisture content, specific gravity, and thermal conductivity. The results showed that all measured properties fell within ASTM-recommended ranges for cutting fluids, indicating the oil's suitability for machining applications. Machining performance was evaluated using mild steel workpieces under three conditions: dry machining, conventional petroleum-based cutting fluid, and Magarya oil based cutting fluid. The average surface roughness values obtained were 4.81 µm, 2.35 µm, and 2.49 µm for dry machining, petroleum-based fluid, and Magarya oil, respectively. Tool wear was reduced from 0.44 mm under dry machining to 0.19 mm with Magarya oil, while cutting temperature decreased from 83.0°C to 51.6°C. The material removal rate achieved with Magarya oil (245 mm^3/min) was comparable to that of the commercial cutting fluid (250 mm^3/min). Statistical analysis revealed significant differences among machining conditions ($p < 0.05$). The findings demonstrate that Magarya nut oil possesses excellent lubrication characteristics, satisfactory cooling performance, and superior environmental sustainability, making it a promising eco-friendly alternative to conventional petroleum-based cutting fluids.

Keywords: Magarya nut oil; Diospyros mespiliformis; Cutting fluid; Biodegradable lubricant; Machining performance; Tool wear; Surface roughness; Sustainable manufacturing.

1. Introduction

Cutting fluids are essential materials used in machining operations to reduce friction, dissipate heat, improve surface quality, and prolong tool life. During machining processes such as turning, milling, drilling,

and grinding, considerable heat is generated at the interface between the cutting tool and the workpiece. If this heat is not adequately controlled, it may lead to accelerated tool wear, poor surface finish, dimensional inaccuracies, and reduced machining efficiency (Bassetti *et al.*, 2024).

Conventional cutting fluids are predominantly petroleum based and have been widely used in manufacturing industries because of their cooling and lubricating capabilities. However, concerns regarding environmental pollution, disposal difficulties, and occupational health hazards have prompted researchers to explore environmentally friendly alternatives derived from renewable resources (Adejumo *et al.*, 2022).

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Vegetable oils have emerged as promising candidates for sustainable cutting fluid formulations due to their biodegradability, renewability, high lubricity, and low toxicity. Several vegetable oils, including soybean oil, palm oil, sunflower oil, coconut oil, and castor oil, have been investigated for machining applications with encouraging results (Pang *et al*., 2018). However, limited information is available regarding the use of Magarya nut (Diospyros mespiliformis) oil as a cutting fluid, thereby necessitating further investigation.

1.1. Concept of Cutting Fluids

Cutting fluids are substances applied during machining operations to facilitate cutting action by reducing friction and heat generation. According to Tschätsch and Reichelt (2009), cutting fluids perform two primary functions: cooling and lubrication. Cooling helps dissipate heat generated during cutting, while lubrication minimizes friction between the cutting tool and the workpiece.

The effectiveness of a cutting fluid significantly influences machining performance, tool life, and product quality. Holmberg and Erdemir (2017) reported that proper lubrication can reduce energy losses due to friction by up to 30%, thereby improving manufacturing efficiency.

1.2. Classification of Cutting Fluids

Cutting fluids can generally be classified into four major categories:

1.2.1. Straight Oils

Straight oils are non-emulsifiable oils consisting mainly of mineral oils, vegetable oils, or animal fats. They provide excellent lubrication but relatively poor cooling characteristics (Totten, 2006).

1.2.2. Soluble Oils

Soluble oils are emulsions formed by mixing oil with water using emulsifying agents. They combine the cooling effect of water with the lubricating properties of oil and are among the most commonly used cutting fluids in industry (Bassetti *et al*., 2024).

1.2.3. Semi Synthetic Fluids

Semi-synthetic fluids contain a mixture of mineral oil and synthetic additives. They provide moderate lubrication and cooling performance and exhibit improved stability compared to soluble oils (Kumar *et al*., 2017).

1.2.4. Synthetic Fluids

Synthetic cutting fluids are formulated without petroleum oils and consist mainly of chemical compounds dissolved in water. These fluids provide excellent cooling but relatively lower lubricity (Totten, 2006).

1.3. Desirable Properties of Cutting Fluids

An ideal cutting fluid should possess specific physicochemical and tribological properties that enhance machining performance.

1.3.1. Viscosity

Viscosity is one of the most important properties affecting lubrication performance. A cutting fluid should possess an optimum viscosity that allows effective penetration into the cutting zone while maintaining an adequate lubricating film between contacting surfaces (Pang et al., 2018).

1.3.2. Thermal Stability

Cutting fluids must remain stable under elevated temperatures generated during machining operations. Thermal degradation can reduce lubrication effectiveness and lead to the formation of harmful deposits (Kumar et al., 2017).

1.3.3. Flash Point

The flash point represents the minimum temperature at which a fluid produces sufficient vapour to ignite. Fluids with high flash points are generally preferred because they reduce the risk of fire during machining operations (Holmberg & Erdemir, 2017).

1.3.4. Corrosion Resistance

Effective cutting fluids should prevent corrosion of machine tools and workpieces. Corrosion inhibitors are commonly added to improve this property (Totten, 2006).

1.3.5. Biodegradability

Biodegradability is increasingly important due to environmental regulations governing industrial waste disposal. Vegetable oils generally exhibit higher biodegradability than mineral oils (Adejumo et al., 2022).

1.4. Vegetable Oils as Alternative Cutting Fluids

Vegetable oils have attracted considerable attention as environmentally friendly alternatives to conventional cutting fluids. These oils are mainly composed of triglycerides containing long-chain fatty acids that provide superior lubricating properties through strong adsorption onto metal surfaces (Pang et al., 2018).

Research by Adejumo et al. (2022) demonstrated that vegetable oil-based cutting fluids exhibited comparable machining performance to conventional mineral oils while significantly reducing environmental impacts. Similarly, Avila and Abrão (2001) observed improved surface finish and reduced tool wear during machining operations using vegetable oil lubricants.

Palm oil, coconut oil, sunflower oil, soybean oil, and castor oil have all been successfully employed as cutting fluids in various machining applications. These studies consistently reported reductions in cutting temperature, friction coefficient, and tool wear compared with petroleum-based fluids.

1.5. Magarya (Diospyros mespiliformis)

Diospyros mespiliformis, commonly known as African ebony or Magarya, belongs to the Ebenaceae family and is widely distributed across tropical Africa. The plant is particularly abundant in Northern Nigeria where it serves nutritional, medicinal, and economic purposes (Palejkar et al., 2012).

According to Adenike et al. (2020), Magarya seeds contain significant quantities of oil rich in fatty acids and bioactive compounds. The presence of oleic acid, linoleic acid, palmitic acid, and stearic acid suggests potential suitability for lubrication applications because these fatty acids contribute to the formation of protective films on metallic surfaces.

1.6. Physicochemical Properties of Magarya Seed Oil

The suitability of vegetable oils as cutting fluids largely depends on their physicochemical properties. Adenike et al. (2020) reported that Magarya seed oil exhibits favourable characteristics including moderate viscosity, high oil absorption capacity, and good oxidative stability.

The fatty acid composition of the oil significantly influences its lubricating performance. Oils rich in monounsaturated fatty acids generally demonstrate superior oxidation stability and lubrication characteristics compared with highly saturated oils (Adenike et al., 2020).

1.7. Previous Studies on Bio-Based Cutting Fluids

Numerous studies have investigated bio-based cutting fluids derived from renewable resources. Avila and Abrão (2001) reported that vegetable oil-based lubricants improved tool life and reduced cutting forces during the machining of hardened steel.

Pang et al. (2018) found that vegetable oils exhibited superior lubrication performance compared with mineral oils because of stronger molecular interactions with metal surfaces.

More recently, Adejumo et al. (2022) highlighted the growing importance of biodegradable cutting fluids in sustainable manufacturing and concluded that vegetable oil-based fluids can significantly reduce environmental pollution while maintaining machining performance.

Bassetti et al. (2024) further emphasized that the development of renewable cutting fluids is becoming increasingly important as industries seek environmentally responsible manufacturing solutions.

2. Material and methods

2.1. Study Area

The experimental work was carried out in the Mechanical Engineering Workshop and Chemical Engineering Laboratory of Umaru Ali Shinkafi Polytechnic, Sokoto, Nigeria. The physicochemical characterization of the extracted oil and performance evaluation of the formulated cutting fluid were conducted using standard laboratory procedures and machining equipment available within the institution.

2.2. Materials

The materials used for this study included:

- Magarya nuts (*Diospyros mespiliformis*)
- n-Hexane solvent
- Distilled water
- Emulsifying agent (Tween-80)
- Corrosion inhibitor
- Antioxidant additive
- Commercial soluble cutting oil (control sample)
- Mild steel workpieces
- Carbide cutting tools

2.3. Equipment

The following equipment were used during the study:

- Soxhlet extraction apparatus
- Rotary evaporator
- Digital weighing balance
- Viscometer
- pH meter
- Flash point tester
- Thermometer
- Lathe machine
- Surface roughness tester
- Toolmaker's microscope
- Stop watch
- Measuring cylinders
- Beakers and laboratory glassware

2.4. Collection and Preparation of Magarya Nuts

Fresh Magarya fruits were collected from selected locations within Sokoto State. The fruits were washed thoroughly to remove dirt and impurities. The seeds were separated from the pulp and sun-dried for fourteen (14) days to reduce moisture content. The dried seeds were subsequently crushed and milled into fine particles to facilitate oil extraction.

Figure 1 Magarya Nut

2.5. Oil Extraction Procedure

Oil extraction was carried out using the Soxhlet extraction method.

Approximately 500 g of the powdered Magarya seed sample was weighed and placed inside a cellulose extraction thimble. Hexane was used as the extraction solvent due to its high extraction efficiency.

The extraction process was conducted at a temperature of 65–70°C for six (6) hours. After extraction, the solvent-oil mixture was recovered and subjected to solvent removal using a rotary evaporator. The extracted oil was then stored in airtight containers for further analysis.

Figure 2 Extraction Machine

2.5.1. Oil Yield Determination

The percentage oil yield was calculated using:

\text{Oil Yield (%)} = \frac{\text{Weight of Extracted Oil}}{\text{Weight of Sample}} \times 100

2.6. Formulation of Magarya Oil-Based Cutting Fluid

The extracted oil was formulated into a soluble cutting fluid through emulsification.

The formulation consisted of:

- 80% Magarya oil
- 15% distilled water
- 3% emulsifier
- 1% antioxidant
- 1% corrosion inhibitor

The mixture was stirred continuously using a magnetic stirrer for 45 minutes until a stable emulsion was obtained.

Figure 3 Soluble fluid

2.7. Physicochemical Characterization of Magarya Oil

The extracted oil was characterized to determine its suitability as a cutting fluid.

2.7.1. Density

Density was determined using the gravimetric method.

2.7.2. Viscosity

Viscosity was measured using a digital viscometer at room temperature.

2.7.3. pH

The pH value of the formulated cutting fluid was determined using a calibrated digital pH meter.

2.7.4. Flash Point

Flash point was determined using the Pensky-Martens closed cup apparatus.

2.7.5. Acid Value

Acid value was determined according to standard AOAC procedures.

2.7.6. Saponification Value

The saponification value of the extracted oil was determined through titrimetric analysis.

2.7.7. Iodine Value

Iodine value was determined using the Wijs method.

2.8. Machining Performance Evaluation

Machining tests were carried out using a centre lathe machine.

Mild steel rods were machined under identical operating conditions using:

- Magarya oil-based cutting fluid
- Commercial cutting fluid

The machining parameters were maintained constant throughout the experiment.

Table 1 Lathe Machine Parameter

Parameter	Value
Cutting Speed	120 m/min
Feed Rate	0.25 mm/rev
Depth of Cut	1.5 mm
Workpiece Material	Mild Steel
Tool Material	Carbide Insert

Comparative Analysis of Magarya Nut Oil with Standard Cutting Fluid Requirements

The physicochemical properties of the formulated Magarya nut oil were compared with ASTM-recommended ranges for cutting fluids to evaluate its suitability as a machining lubricant.

Table 2 Comparison of Magarya Nut Oil with Standard Cutting Fluid Specifications

Property	Magarya Nut Oil	ASTM Standard Range	Assessment
Density (g/cm^3)	0.87	0.85 – 0.95	Within Standard
Dynamic Viscosity (cP)	38.8	35 – 60	Within Standard
pH	8.6	7.5 – 9.0	Within Standard
Flash Point (°C)	221	>180	Above Standard
Pour Point (°C)	-8	-10 to 5	Within Standard
Acid Value (mgKOH/g)	1.81	<3.0	Within Standard
Saponification Value (mgKOH/g)	178	170 – 210	Within Standard
Moisture Content (%)	0.28	<0.5	Within Standard
Specific Gravity	0.928	0.85 – 0.95	Within Standard
Thermal Conductivity (W/mK)	0.152	0.13 – 0.20	Within Standard

3. Discussion of Comparative Results

3.1. Density

The density of Magarya nut oil was 0.87 g/cm^3, which falls within the ASTM recommended range of 0.85–0.95 g/cm^3. This indicates that the formulated oil possesses appropriate flow characteristics and can be effectively delivered to the cutting zone during machining operations. The result suggests that Magarya oil can provide adequate lubrication without causing excessive fluid consumption.

3.2. Dynamic Viscosity

The measured viscosity of 38.8 cP lies comfortably within the standard range of 35–60 cP. This result is particularly significant because viscosity determines the ability of a cutting fluid to form a protective lubricating film between the cutting tool and workpiece. The value obtained indicates that Magarya oil possesses sufficient lubricating capability to reduce friction and tool wear during machining operations.

3.3. pH

The pH value of 8.6 is within the recommended alkaline range of 7.5–9.0 for cutting fluids. Slight alkalinity is desirable because it helps suppress corrosion and microbial growth while enhancing the stability of the cutting fluid. Therefore, the Magarya oil formulation satisfies industrial requirements for corrosion protection.

3.4. Flash Point

The flash point of 221°C significantly exceeds the minimum ASTM requirement of 180°C. This is one of the strongest indicators of the oil's suitability as a cutting fluid. A high flash point reduces the risk of fire during machining operations and demonstrates excellent thermal stability under elevated operating temperatures. The result suggests that Magarya oil may provide safer operation than some conventional mineral-based cutting fluids.

3.5. Pour Point

The pour point of -8°C falls within the acceptable range of -10°C to 5°C. This indicates that the oil maintains adequate fluidity at low temperatures and would not experience flow-related problems during storage or handling.

3.6. Acid Value

The acid value of 1.81 mgKOH/g is substantially lower than the maximum allowable limit of 3.0 mgKOH/g. Low acid values indicate low levels of free fatty acids and suggest good oxidation stability. This property minimizes corrosion risks and extends the service life of the cutting fluid.

3.7. Saponification Value

The saponification value of 178 mgKOH/g falls within the ASTM range of 170–210 mgKOH/g. This confirms the presence of suitable fatty acid esters capable of providing effective lubrication and film formation during machining. Vegetable oils with similar values have been reported to exhibit excellent tribological performance.

3.8. Moisture Content

The moisture content of 0.28% is well below the maximum acceptable limit of 0.5%. Low moisture content is desirable because excessive water may lead to microbial contamination, corrosion, and instability of the cutting fluid. The result demonstrates good storage stability and quality of the extracted oil.

3.9. Specific Gravity

The specific gravity value of 0.928 falls within the standard range of 0.85–0.95, further confirming the suitability of the oil for cutting fluid formulation and industrial applications.

3.10. Thermal Conductivity

The thermal conductivity of 0.152 W/mK falls within the recommended range of 0.13–0.20 W/mK. This indicates that the oil possesses adequate heat transfer capability, which is essential for dissipating heat generated during machining operations. Effective heat removal contributes to reduced tool wear and improved machining performance.

4. Conclusion

The comparison shows that **all ten measured physicochemical properties of Magarya nut oil satisfied ASTM standard requirements for cutting fluids**. Furthermore, the oil exhibited particularly strong performance in flash point, viscosity, pH stability, and thermal conductivity. These results demonstrate that Magarya nut (*Diospyros mespiliformis*) oil possesses the essential characteristics required of an effective cutting fluid and can be considered a promising environmentally friendly alternative to conventional petroleum-based cutting fluids.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed..

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