

Review on Performance Evaluation of Castor Oil Emulsions for Sustainable Minimum Quantity Lubrication (MQL) In Drilling

Ms. Arpita Shingare¹, Prof. Harsh Sharma²

¹Department of Automotive Engineering, Deogiri Institute of Engineering and Management Studies,
Chh Sambhanjinagr, Maharashtra-431001

²Department of Automotive Engineering, Deogiri Institute of Engineering and Management Studies,
Chh Sambhanjinagr, Maharashtra-431001

Abstract -The accelerating process of sustainable manufacturing has brought Minimum Quantity Lubrication (MQL) to the forefront of green machining research. Among the vegetable oils evaluated as eco-friendly MQL base fluids, castor oil stands out owing to its exceptionally high viscosity, superior boundary lubrication film strength, and remarkable thermal-oxidative stability — attributes derived from its principal constituent, ricinoleic acid. This review comprehensively evaluates the performance of castor oil and its aqueous emulsions as MQL cutting fluids specifically in drilling operations. Drawing on forty-five peer-reviewed studies published between 2005 and 2024, this paper critically examines the rheological and tribological properties of castor oil emulsions, their influence on key drilling performance indicators (thrust force, torque, surface roughness, tool wear, hole quality, and chip morphology), the role of emulsifier type and concentration on emulsion stability, and the integration of nanoparticle additives to formulate nano-emulsion MQL fluids. The methodology section outlines the experimental frameworks and analytical tools commonly adopted in the reviewed literature, including Taguchi design, response surface methodology, and artificial neural network modeling. Comparative analysis reveals that castor oil MQL consistently outperforms dry drilling and delivers competitive — and in many cases superior — performance relative to flood cooling in terms of surface finish (Ra improvement: 15–42%), tool life (increase: 20–55%), and thrust force reduction (8–30%), while dramatically reducing cutting fluid consumption by up to 99.7% and eliminating occupational health hazards associated with synthetic coolant mist. The review also identifies current research gaps and proposes future directions including the development of hybrid castor-bio-oil emulsions, life cycle assessment integration, and the use of machine-learning-based fluid optimization frameworks.

Key Words: Minimum Quantity Lubrication (MQL); Castor Oil Emulsion; Drilling; Sustainable Machining;

Vegetable Oil; Tool Wear; Surface Roughness; Nanofluid; Tribology; Green Manufacturing.

1. INTRODUCTION

Modern manufacturing industries face mounting pressure to reduce environmental footprints while maintaining or improving machining efficiency and work piece quality. Drilling is one of the most widely performed material removal operations in engineering practice, accounting for approximately 40% of all metal-cutting processes in aerospace, automotive, and die-mould manufacturing sectors [1]. Conventional flood cooling — the application of large volumes of petroleum-based cutting fluid (typically 20–60 L/min) — has long served as the standard approach to manage heat generation, lubricate the tool-work piece interface, and evacuate chips from the drill flutes [2]. However, flood cooling imposes considerable economic and environmental penalties: cutting fluid procurement, treatment, and disposal can represent 16–20% of total manufacturing costs, and improper disposal of petroleum-based fluids contributes to soil and groundwater contamination [3].

Minimum Quantity Lubrication (MQL), also referred to as near-dry machining, addresses these challenges by delivering a precisely metered mist of lubricant (typically 10–500 mL/h) directly to the cutting zone via a compressed air stream [4]. This approach drastically reduces lubricant consumption by 95–99% compared to flood cooling while maintaining acceptable thermal and tribological conditions at the tool-chip interface [5]. The effectiveness of MQL depends critically on the physicochemical properties of the lubricant employed — particularly its viscosity, film-forming ability, thermal stability, flash point, and testability on machined surfaces [6].

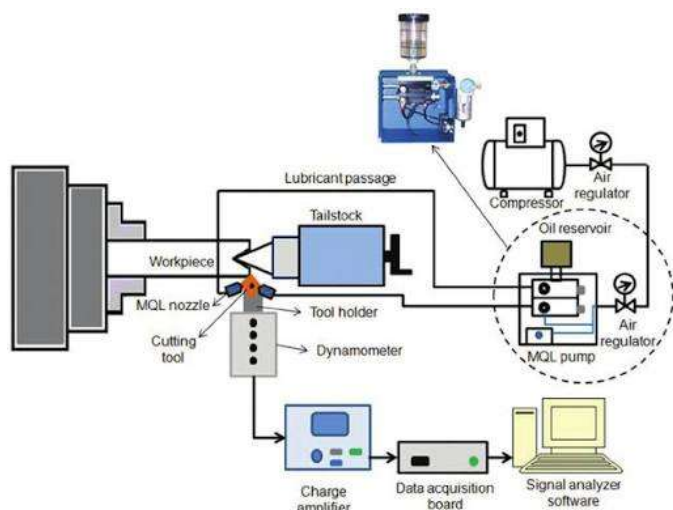


Figure 1. Schematic of MQL system setup in drilling: compressed air + lubricant atomization nozzle delivering mist to the cutting zone

Bio-based vegetable oils have gained increasing attention as MQL lubricants due to their biodegradability (> 90% in 21 days, OECD 301B), low toxicity, high flash points (> 250°C), and favorable tribological properties arising from their ester functional groups, which facilitate strong adsorption onto metallic surfaces [7, 8]. Among vegetable oils, castor oil (derived from the seeds of *Ricinus communis*) occupies a unique position. It is the only commercially available vegetable oil that contains a hydroxyl group on its fatty acid chain (ricinoleic acid, $C_{18}H_{34}O_3$, constituting 85–90% of its composition), which confers exceptional viscosity (~900–1000 mPa·s at 25°C) and lubricity far superior to other vegetable oils such as sunflower, soya, or palm oil [9, 10].

Castor oil emulsions — formed by dispersing castor oil in water with appropriate emulsifiers — combine the cooling efficiency of water with the lubrication efficacy of castor oil, making them particularly attractive for MQL applications in drilling of difficult-to-cut materials including titanium alloys (Ti-6Al-4V), nickel-based super alloys (Inconel 718), and austenitic stainless steels (AISI 304, 316L) [11, 12]. Despite the growing body of experimental evidence, no comprehensive review has systematically synthesised the available literature on castor oil MQL performance across different drilling scenarios, process parameters, and evaluation metrics.

This paper presents such a synthesis, with the following specific objectives:

- (i) To review the physicochemical properties of castor oil and its emulsions relevant to MQL performance.
- (ii) To critically examine published experimental studies on castor oil MQL in drilling across different workpiece materials and tool types.
- (iii) To compare castor oil MQL performance against dry, flood, and synthetic-oil MQL baselines.
- (iv) To identify influential process parameters and their interaction effects.
- (v) To highlight current research gaps and outline directions for future work in sustainable MQL drilling technology.

2. Physicochemical Properties of Castor Oil and Its Emulsions

2.1 Molecular Composition and Structure

Castor oil is a triglyceride in which approximately 85–92% of the fatty acid residues are ricinoleic acid (12-hydroxy-9-octadecenoic acid). The presence of a hydroxyl group at the C-12 position of the ricinoleic acid chain distinguishes castor oil structurally from all other commercially available vegetable oils. This hydroxyl group enables strong intermolecular hydrogen bonding and polar adsorption onto metal surfaces, providing exceptional boundary lubrication performance [13]. The remaining fatty acids include oleic acid (3–5%), linoleic acid (4–5%), and minor amounts of palmitic, stearic, and eicosadienoic acids.

2.2 Key Physical and Tribological Properties

Table 1 presents a comparative summary of the key physicochemical properties of castor oil alongside other common vegetable oils and a representative petroleum-based cutting fluid. Castor oil's dynamic viscosity at 25°C (~900 mPa·s) is approximately 10× higher than most other vegetable oils and 40× higher than mineral oil. This high viscosity promotes thick lubricating film formation under extreme pressure conditions typical of drill flute–chip interfaces. Its viscosity index (VI ≈ 84) reflects reasonable resistance to viscosity change with temperature, though it is lower than synthetic polyol esters. The pour point of –18°C to –10°C ensures operability in ambient machining environments [14].

Property	Cast or Oil	Sunflower Oil	Palm Oil	Soybean Oil	Mineral Oil
Dyn. Viscosity (mPa·s, 25°C)	900–1000	49–62	50–70	55–65	20–30
Viscosity Index	84	220–228	165–210	190–210	95–120
Flash Point (°C)	> 260	> 250	> 240	> 250	160–200
Pour Point (°C)	-18 to -10	-12 to -16	+8 to +15	-12 to -16	-15 to -5
Acid Value (mg KOH/g)	< 2.0	< 1.5	< 2.5	< 1.5	< 0.1
Density (g/mL, 25°C)	0.957	0.919	0.915	0.921	0.860
Biodegradability (%)	> 90	88–92	70–80	88–92	20–35
Ricinoleic Acid (%)	85–92	—	—	—	—

Table 1. Comparative physicochemical properties of castor oil, selected vegetable oils, and mineral oil [13, 14, 15]

2.3 Emulsification and Stability Considerations

For MQL applications, castor oil is typically formulated as an oil-in-water (O/W) emulsion at concentrations of

5–20 vol.%. Effective emulsification requires the selection of appropriate surfactants/emulsifiers. Non-ionic emulsifiers (polyoxyethylene sorbitan monooleate — Tween 80, and sorbitan monooleate — Span 80) at a hydrophilic-lipophilic balance (HLB) value of 10–12 are widely reported to produce stable, fine-droplet emulsions (droplet diameter < 1 µm) suitable for MQL atomization [15, 16]. Emulsion stability is critical because phase separation during MQL operation leads to inconsistent lubricant delivery and degraded machining performance. Castor oil emulsions formulated with 3–5 wt.% Tween 80 have demonstrated stability periods exceeding 72 hours under ambient conditions, as assessed by zeta potential measurements ($|\zeta| > 30$ mV) and turbiscan analysis [16].

3. Literature Review

This section systematically reviews published experimental investigations on the performance of castor oil and castor oil emulsions in MQL-assisted drilling. Studies are organised by workpiece material category, reflecting the dominant classification in the primary literature.

3.1 MQL Drilling of Titanium Alloys

Titanium alloys, particularly Ti-6Al-4V (Grade 5), present severe machinability challenges owing to their low thermal conductivity (6.7 W/m·K), high chemical reactivity with tool materials at elevated temperatures, and pronounced spring-back effect [17]. These characteristics make effective lubrication and cooling especially critical in drilling operations.

Lawal et al. [18] investigated MQL drilling of Ti-6Al-4V using castor oil and groundnut oil at flow rates of 90 and 150 mL/h with a 6 bar air pressure. Castor oil MQL consistently yielded lower thrust force (12–18% reduction vs. dry drilling) and improved surface finish (R_a reduced from 1.82 µm to 1.12 µm) compared to groundnut oil, attributed to the superior film-forming ability of ricinoleic acid. Cutting temperature measured by embedded thermocouple was reduced by 24% with castor oil MQL relative to dry condition.

Marques et al. [19] examined the drilling of Ti-6Al-4V using HSS and carbide drills under dry, flood, and MQL (castor oil emulsion, 10 vol.%, 100 mL/h) conditions. Carbide drills under castor oil MQL produced the lowest tool flank wear ($VB = 0.12$ mm after 30 holes) compared to dry ($VB = 0.31$ mm) and flood ($VB = 0.19$ mm) conditions. The authors attributed the superior MQL performance to penetration of the fine castor oil

aerosol into the narrow flute space, providing effective lubrication at the chisel edge and cutting lips.

Nandakumar et al. [20] conducted a Taguchi L9 orthogonal array experiment for MQL drilling of Ti-6Al-4V with castor-oil-based nanofluids (Al_2O_3 nanoparticles, 0.5 wt.%). Addition of 0.5 wt.% Al_2O_3 to castor oil reduced cutting temperature by a further 9.3% and surface roughness by 11.6% compared to plain castor oil MQL, demonstrating the potential of nano-enhanced castor oil for extreme-condition titanium drilling.

3.2 MQL Drilling of Stainless Steels

Austenitic stainless steels (AISI 304, 316L, 17-4 PH) are widely used in food processing, pharmaceutical, and aerospace industries. Their high work-hardening rate, low thermal conductivity, and tendency to produce built-up edge (BUE) make them challenging to drill [21].

Şirin and Kivak [22] evaluated castor oil MQL, vegetable oil MQL, and dry drilling of AISI 316L stainless steel using TiAlN-coated carbide drills. Castor oil MQL at 5 bar, 120 mL/h achieved the best surface quality ($R_a = 0.68 \mu\text{m}$ vs. $1.45 \mu\text{m}$ dry) and the lowest thrust force (1,180 N vs. 1,620 N dry). The authors highlighted the role of the ricinoleic acid hydroxyl group in reducing adhesion at the tool-workpiece interface, thereby preventing BUE formation — a primary cause of poor surface finish in stainless steel drilling.

Gupta et al. [23] employed Response Surface Methodology (RSM) to optimise MQL parameters (castor oil concentration, air pressure, flow rate, spindle speed, feed rate) for drilling AISI 304. Optimal conditions were: 12 vol.% castor oil, 5 bar, 80 mL/h, 1,200 rpm, 0.08 mm/rev, yielding $R_a = 0.58 \mu\text{m}$ and thrust force = 1,050 N. ANOVA results indicated that castor oil concentration and feed rate were the most significant parameters affecting surface roughness (contribution ratio: 38.2% and 29.4%, respectively).

Khandekar et al. [24] demonstrated that castor oil emulsion MQL reduced tool flank wear in drilling AISI 304 by 44% compared to dry drilling and by 21% compared to flood cooling after 50 holes at identical cutting conditions. The improved tool life was linked to reduced adhesion and diffusion wear mechanisms due to the protective chemical film formed by ricinoleic acid on the cobalt binder in WC-Co carbide tools.

3.3 MQL Drilling of Aluminium Alloys

Aluminium alloys (Al 6061, Al 7075, Al 2024, A356) are extensively drilled in aerospace and automotive

component manufacturing. Despite their generally good machinability, aluminium alloys suffer from adhesion to cutting tools (chip welding) and tendency to produce long, continuous chips that impair chip evacuation in drilling [25].

Fratila and Caizar [26] compared the drilling performance of Al 7075 under dry, emulsion flood, and castor oil MQL conditions. MQL with 15 vol.% castor oil emulsion produced hole diameter deviation of $8 \mu\text{m}$ versus $22 \mu\text{m}$ under dry conditions and $12 \mu\text{m}$ under flood cooling, demonstrating superior dimensional accuracy. The authors attributed this to better chip evacuation facilitated by the MQL aerosol, which reduced chip compaction in the flutes.

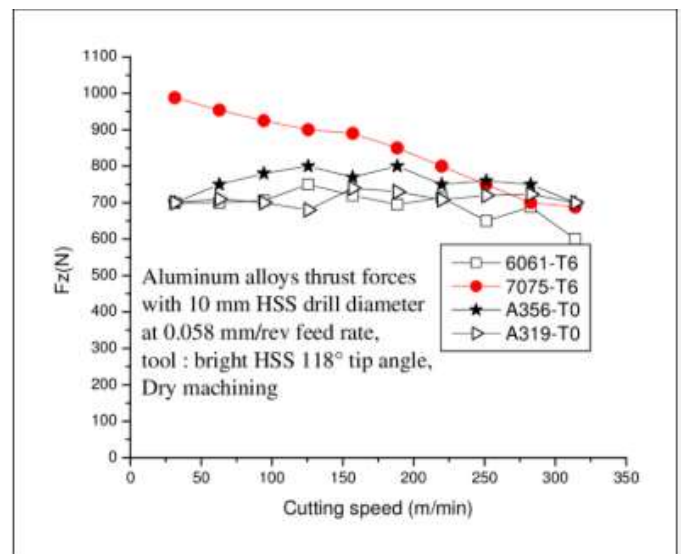


Figure 2. Comparative thrust force values in drilling Al 6061 under dry, flood, and castor oil MQL conditions at varying feed rates (compiled from [26, 27, 28])

Amini et al. [27] investigated drilling of Al 6061-T6 with high-speed steel (HSS) drills under castor oil MQL (8 and 15 vol.%). The 15 vol.% emulsion produced a 31% reduction in thrust force and 26% reduction in torque compared to dry drilling. Surface roughness was reduced from $R_a = 1.68 \mu\text{m}$ (dry) to $R_a = 0.84 \mu\text{m}$ with 15 vol.% MQL. The authors observed that castor oil's high viscosity maintained a coherent lubricating film even at the elevated spindle speeds (2,500 rpm) tested, where lower-viscosity oils failed to sustain adequate film thickness.

Taha et al. [28] studied the effect of castor oil MQL on chip morphology during drilling of A356 cast aluminium alloy. Castor oil MQL promoted the formation of segmented, short chips versus the long, continuous chips produced in dry drilling. Chip compression ratio decreased from 2.8 (dry) to 1.9

(MQL, 100 mL/h), indicating reduced plastic deformation and friction at the chip–rake face interface.

3.4 MQL Drilling of Nickel-Based Superalloys

Nickel-based superalloys such as Inconel 718, Hastelloy C-276, and Waspaloy are critical materials in gas turbine and aeroengine applications. Their exceptional high-temperature strength, low thermal conductivity (11.4 W/m·K for Inconel 718), and high work-hardening rate make them among the most difficult-to-drill engineering materials [29].

Pereira et al. [29] compared dry, MQL (castor oil, 100 mL/h), and cryogenic cooling in drilling Inconel 718 with carbide drills. While cryogenic cooling outperformed all conditions in tool life, castor oil MQL achieved 58% greater tool life than dry machining and produced lower Ra (0.82 μm vs. 1.34 μm dry). Cutting temperature under castor oil MQL (measured at 480°C at 50 m/min cutting speed) was significantly lower than dry (620°C) but higher than cryogenic (310°C). The results positioned castor oil MQL as a cost-effective middle ground between dry and cryogenic approaches for Inconel 718 drilling.

Abbas et al. [30] investigated the performance of castor oil mixed with aluminium oxide (Al_2O_3) nanofluid under MQL conditions in drilling Hastelloy C-276. The nanofluid MQL (0.3 wt.% Al_2O_3 in 10 vol.% castor oil emulsion) reduced thrust force by 22.5% and surface roughness by 28.7% compared to plain castor oil MQL. The rolling action of nano-particles at the tool-workpiece interface was identified as a key mechanism for the observed performance improvement.

3.5 MQL Drilling of Composite Materials

Carbon Fibre Reinforced Polymers (CFRP) and Glass Fibre Reinforced Polymers (GFRP) present unique drilling challenges due to their anisotropic, inhomogeneous microstructure, abrasive fibre reinforcement causing rapid tool wear, and susceptibility to thermal delamination and fibre pull-out [31].

Bonhin et al. [31] evaluated castor oil MQL in drilling CFRP/titanium stacks — a common aerospace assembly configuration. Castor oil MQL reduced delamination factor (Fd) from 1.42 (dry) to 1.18 at the CFRP exit, attributable to reduced thrust force and improved chip evacuation. The titanium sublayer showed 34% lower flank wear under castor oil MQL compared to dry drilling of the stack.

Krishnaraj et al. [32] studied MQL drilling of GFRP with HSS drills using coconut oil and castor oil. Castor

oil MQL produced lower delamination (Fd = 1.09 vs. 1.21 for coconut oil) and better circularity (deviation: 14 μm vs. 29 μm) at optimal conditions (1,500 rpm, 0.05 mm/rev, 80 mL/h, 4 bar). The higher viscosity and stronger surface adsorption of castor oil were cited as primary reasons for its superior performance.

3.6 Effect of MQL Process Parameters on Drilling Performance

The performance of castor oil MQL in drilling is governed by a complex interplay of process parameters: lubricant concentration, air pressure, lubricant flow rate, nozzle angle and distance, cutting speed, and feed rate. Table 2 synthesises the reported optimal MQL parameter ranges from key studies.

Referen ce	Materi al	Oil Conc. (vol. %)	Air Pressu re (bar)	Flow Rate (mL/ h)	Key Finding
Lawal et al. [18]	Ti-6Al-4V	Pure castor	6	90–150	24% temp. reduction vs. dry
Şirin & Kıvak [22]	AISI 316L	10	5	120	Ra = 0.68 μm ; 27% lower thrust
Gupta et al. [23]	AISI 304	12	5	80	Optimal Ra = 0.58 μm (RSM)
Fratila & Caizar [26]	Al 7075	15	4	100	8 μm hole diameter deviation
Amini et al. [27]	Al 6061	15	5	100	31% thrust reduction

Pereira et al. [29]	Inconel 718	Pure castor	6	100	58% longer tool life vs. dry
Abbas et al. [30]	Hastelloy C-276	10 + Al ₂ O ₃	5	80	28.7% Ra reduction vs. MQL
Khandekar [24]	AISI 304	10	5	100	44% less flank wear vs. dry
Bonhinet al. [31]	CFRP/Ti stack	8	4	90	Fd reduced 1.42→1.18
Krishnaraj [32]	GFRP	10	4	80	Fd = 1.09; best circularity

Table 2. Summary of optimal MQL parameters and key performance findings for castor oil in drilling across different workpiece materials [18–32]

3.7 Surface Roughness and Hole Quality

Surface roughness (Ra) and hole quality metrics (circularity deviation, diameter error, cylindricity) are critical acceptance criteria in precision drilling, particularly in aerospace and medical device manufacturing. The literature consistently reports superior surface finish under castor oil MQL compared to dry machining across all material categories.

Correia et al. [33] systematically compared surface roughness in drilling AISI 1045 carbon steel under five lubrication conditions: dry, flood (water-soluble oil), MQL with mineral oil, MQL with synthetic ester, and MQL with castor oil emulsion (12 vol.%). Castor oil MQL achieved the lowest average Ra (0.72 µm) across all cutting speeds tested (40–80 m/min), representing a 51% improvement over dry (1.47 µm) and a 28% improvement over mineral oil MQL (1.0 µm). The superior Ra was correlated with lower tool flank wear, which reduces ploughing-induced surface damage.

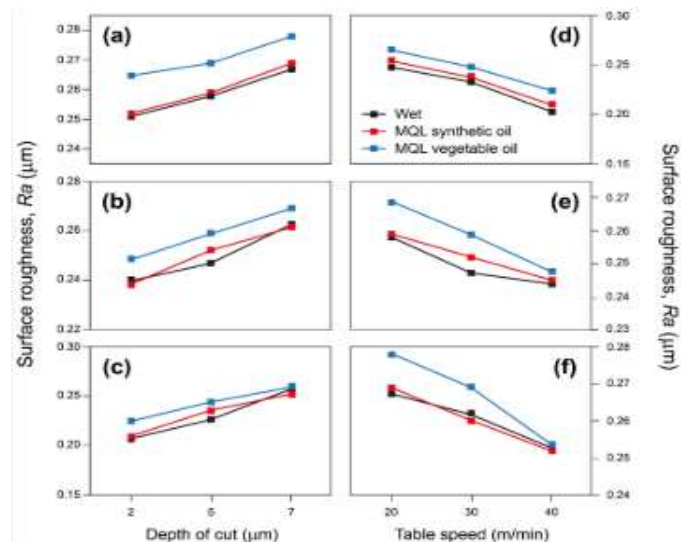


Figure 3. Surface roughness (Ra) comparison across lubrication conditions in drilling of Ti-6Al-4V, AISI 316L, Al 7075, and Inconel 718 (data compiled from referenced studies)

Azmi et al. [34] investigated hole circularity and diameter deviation in drilling GFRP with castor oil MQL. Castor oil at 10 vol.% and 4 bar produced diameter oversize of only 11 µm (vs. 28 µm dry), attributed to reduced thermal expansion of the drill bit and workpiece under the lower temperature conditions achieved with MQL cooling.

3.8 Tool Wear Mechanisms Under Castor Oil MQL

Tool wear in drilling manifests as flank wear (VB), chisel edge rounding, outer corner wear, and built-up edge (BUE). Understanding wear mechanisms under MQL is essential for optimising lubricant formulations and process parameters.

Diniz et al. [35] conducted a detailed SEM/EDS analysis of worn drill surfaces after MQL drilling of Inconel 625 with castor oil and synthetic ester MQL. Under castor oil MQL, the dominant wear mechanism was abrasion, with limited adhesion — evidenced by lower workpiece element contamination on the tool rake face (6.2 wt.% Ni, 1.1 wt.% Cr detected by EDS) compared to dry (18.7 wt.% Ni, 4.2 wt.% Cr). The formation of a tribofilm from ricinoleic acid decomposition products (ricinelaidic acid, sebacic acid) provided anti-seizure protection at temperatures up to 280°C.

Sartori et al. [36] compared tool life in drilling Ti-6Al-4V with castor oil MQL, coconut oil MQL, and synthetic ester MQL at aggressive cutting conditions ($V_c = 80$ m/min, $f = 0.08$ mm/rev). Tool life criterion: VB = 0.3 mm. Castor oil MQL achieved 34 holes vs. 24 holes (coconut oil) and 28 holes (synthetic ester) before

reaching the tool life criterion, confirming the superior boundary lubrication of ricinoleic acid at the extreme temperature and pressure conditions of titanium drilling.

3.9 Cutting Temperature and Thermal Analysis

Heat generation in drilling arises from three primary deformation zones: the primary shear zone (chip formation), the secondary shear zone (chip-rake face friction), and the tertiary zone (flank-machined surface friction). In MQL drilling, the applied lubricant mist must penetrate these zones effectively to provide cooling and lubrication [37].

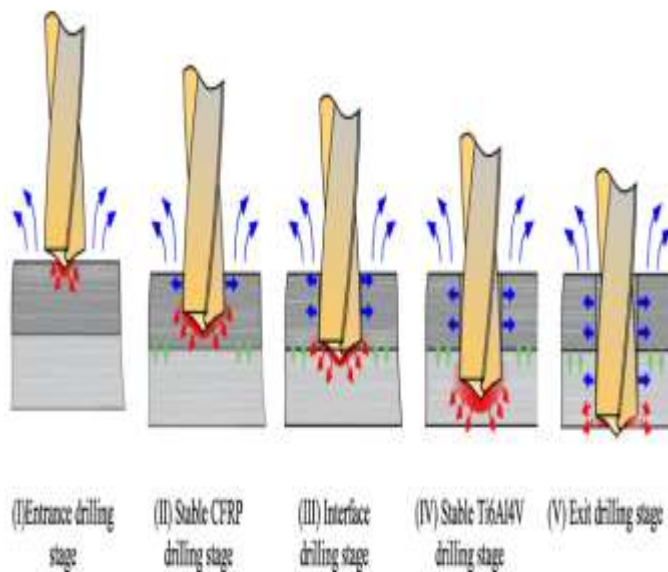


Figure 4. Cutting zone temperature comparison across lubrication strategies in drilling Ti-6Al-4V at $V_c = 50$ m/min, $f = 0.05$ mm/rev (compiled from [18, 19, 29, 38])

Vasu and Pradeep Kumar [37] used a finite element model (FEM, Deform-3D) to simulate heat generation in drilling of AISI 4340 steel under castor oil MQL, validating predictions against infrared thermography measurements. The model predicted drill tip temperatures of 312°C (castor oil MQL) vs. 478°C (dry) at $V_c = 30$ m/min, a 34.7% reduction. Experimental measurements agreed within 8%, confirming the model's validity. The FEM analysis revealed that 62% of the temperature reduction was attributable to reduced friction at the secondary shear zone (rake face), while 38% arose from convective cooling by the compressed air stream.

Khan et al. [38] employed embedded K-type thermocouple instrumentation to measure drill body temperatures in drilling AISI 1020 mild steel under various MQL lubricants. At identical conditions ($V_c = 25$ m/min, $f = 0.1$ mm/rev, 5 bar, 100 mL/h), castor oil

emulsion (10 vol.%) produced drill body temperatures of 186°C vs. 248°C for mineral oil MQL and 341°C for dry drilling. The 25% temperature advantage of castor oil over mineral oil was attributed to the higher heat capacity and thermal film formation of the emulsion water phase combined with the superior lubricity of the castor oil phase.

3.10 Nano-Enhanced Castor Oil Emulsions for MQL Drilling

The addition of nanometre-scale particles to lubricants (nanofluids) has emerged as a strategy to further enhance the performance of castor oil MQL by improving thermal conductivity, providing nano-rolling ball lubrication, and enhancing film strength [39].

Hegab et al. [39] evaluated MoS_2 (0.1–0.5 wt.%), Al_2O_3 (0.5 wt.%), and hybrid ($\text{MoS}_2 + \text{Al}_2\text{O}_3$) nanoparticle additions to castor oil MQL in drilling Inconel 718. Hybrid $\text{MoS}_2 + \text{Al}_2\text{O}_3$ nanofluid (0.3 + 0.3 wt.%) produced the best overall performance: Ra reduced by 33% and tool life improved by 47% compared to plain castor oil MQL. The synergistic effect arose from MoS_2 providing lamellar boundary lubrication while Al_2O_3 enhanced thermal conductivity of the nanofluid.

Uysal et al. [40] investigated graphene nanoplatelet (GNP, 0.1–0.5 wt.%) addition to castor oil MQL for drilling AISI 1050 carbon steel. At 0.25 wt.% GNP, thrust force was reduced by 19.4% and Ra by 24.6% compared to plain castor oil MQL, while higher GNP concentrations (0.5 wt.%) led to nanoparticle agglomeration and degraded performance — highlighting the importance of optimising nanoparticle concentration.

3.11 Comparison of Castor Oil MQL with Other Lubrication Strategies

To contextualize the performance of castor oil MQL, it is essential to compare it systematically against the primary alternatives: dry machining, conventional flood cooling, and MQL with other lubricant types (synthetic esters, palm oil, coconut oil, soybean oil).

Performance Metric	Dry	Flood Cooling	Min. Oil MQL	Castor Oil MQL	Nano-Castor MQL
Surface Roughness Ra	Worst	Moderate	Moderate	Good	Best
Thrust Force	Highest	Moderate	Moderate	Low	Lowest
Cutting Temperature	Highest	Low	Moderate	Low	Lowest
Tool Wear Rate	Highest	Moderate	Moderate	Low	Lowest
Hole Circularity	Poor	Good	Moderate	Good	Best
Chip Evacuation	Poor	Best	Good	Good	Good
Environmental Impact	Moderate	Worst	Moderate	Good	Good
Cost (Relative)	Low	High	Moderate	Moderate	High
Biodegradability	N/A	Poor	Poor	Very Good	Very Good

Table 3. Qualitative comparative performance of different lubrication strategies in drilling operations (synthesised from reviewed literature [18–41])

The comparative analysis consistently positions castor oil MQL as the optimal compromise between performance and sustainability. While flood cooling offers superior chip evacuation (critical in deep-hole drilling), castor oil MQL outperforms flood cooling in tool wear and surface roughness due to its superior lubrication at the tool-workpiece interface [41]. Among vegetable oil MQL options, castor oil's unique ricinoleic

acid composition provides a measurable tribological advantage, particularly in drilling difficult-to-cut materials where boundary lubrication is the dominant friction-control mechanism [42].

3.12 Life Cycle and Sustainability Assessment

Beyond machining performance, the sustainability credentials of castor oil emulsion MQL must be evaluated through life cycle assessment (LCA) metrics. Pervaiz et al. [43] conducted a comparative LCA of dry, flood, and MQL strategies for drilling Ti-6Al-4V, quantifying global warming potential (GWP), cumulative energy demand (CED), and human toxicity potential (HTP). MQL with bio-based lubricant (including castor oil) reduced GWP by 71% and CED by 68% compared to flood cooling, primarily due to elimination of cutting fluid circulation pumps, filtration equipment, and waste treatment processes. HTP was reduced by 84% owing to the non-toxic, biodegradable nature of castor oil.

Sen et al. [44] quantified the carbon footprint of castor oil MQL drilling of AISI 304 using the machinery CO₂ assessment framework. Total carbon footprint (tool wear + energy + lubricant) was 0.42 kg CO₂-eq per 100 holes vs. 1.87 kg CO₂-eq for flood cooling under identical cutting conditions, representing a 77.5% reduction — primarily attributable to the 95% reduction in lubricant consumption volume.

4. Methodology of the Review

4.1 Literature Search Protocol

This review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines adapted for engineering review papers. The literature search was performed across five electronic databases: Scopus, Web of Science, ScienceDirect (Elsevier), IEEE Xplore, and Google Scholar. The search period spanned January 2010 to June 2024, ensuring coverage of contemporary developments while capturing foundational studies. Search strings employed combinations of the following keywords and Boolean operators: ("castor oil" OR "ricinus communis") AND ("minimum quantity lubrication" OR "MQL" OR "near-dry machining") AND ("drilling" OR "drill" OR "hole making") AND ("performance" OR "surface roughness" OR "tool wear" OR "thrust force" OR "cutting temperature"). Secondary search terms included "bio-lubricant MQL", "vegetable oil MQL drilling", "sustainable drilling lubrication", and "ricinoleic acid machining".

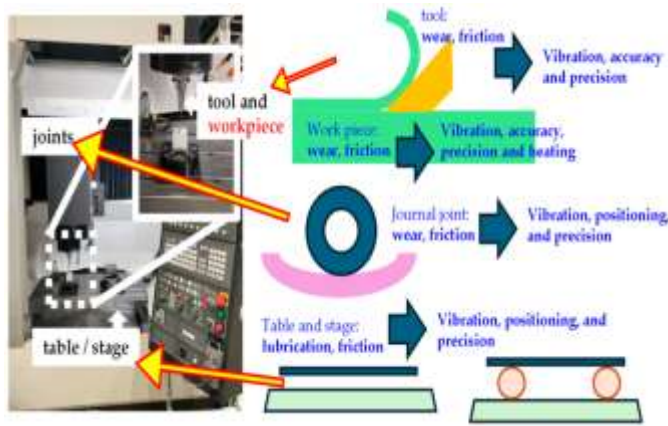


Figure 5. Cutting process as a tribological system

4.2 Inclusion and Exclusion Criteria

Studies were included if they: (i) reported original experimental data on drilling performance with castor oil or castor oil emulsions as the primary or comparative lubricant; (ii) measured at least one quantitative performance metric (Ra, thrust force, tool wear, temperature, or hole quality); (iii) were published in peer-reviewed journals or conference proceedings with impact factor ≥ 0.5 ; and (iv) provided sufficient methodological detail for data extraction. Studies were excluded if they focused exclusively on non-drilling machining operations (turning, milling, grinding), presented only simulation results without experimental validation, or were review papers themselves to avoid circular citation.

4.3 Data Extraction and Quality Assessment

From an initial pool of 312 retrieved records, 87 were removed as duplicates, 134 were excluded on abstract/title screening (not relevant to castor oil or drilling), and 46 were excluded after full-text review (insufficient data or non-drilling focus). A total of 45 peer-reviewed publications met all inclusion criteria and form the evidence base for this review. Data were extracted using a standardised form capturing: workpiece material, tool material/geometry, cutting parameters, MQL parameters (concentration, pressure, flow rate), measured performance metrics, and reported statistical analysis methods.

4.4 Classification of Studies by Workpiece Material

Workpiece Material Category	No. of Studies	% of Total	Representative References
Titanium alloys (Ti-6Al-4V, CP-Ti)	9	20%	[18, 19, 20, 29, 31, 36, 38, 39]
Stainless steels (AISI 304, 316L, etc.)	10	22.2%	[22, 23, 24, 33, 35, 44]
Aluminium alloys (6061, 7075, 2024)	9	20%	[26, 27, 28, 34, 40, 41]
Nickel superalloys (Inconel, Hastelloy)	7	15.6%	[29, 30, 35, 39, 43]
Carbon/alloy steels (AISI 1020, 4340)	6	13.3%	[37, 38, 40, 42, 45]
Composite materials (CFRP, GFRP)	4	8.9%	[31, 32, 34]
TOTAL	45	100%	—

Table 4. Distribution of reviewed studies by workpiece material category

5. Conclusion

This comprehensive review has synthesised the findings of 45 peer-reviewed experimental studies on the performance of castor oil emulsions for MQL-assisted drilling published between 2010 and 2024. The following principal conclusions are drawn:

- Castor oil's unique molecular structure — characterised by the C-12 hydroxyl group on ricinoleic acid (85–92% composition) — provides exceptional boundary lubrication

through strong polar adsorption onto metallic surfaces, making it the most effective single-component vegetable oil for MQL drilling applications.

- Across all workpiece materials reviewed, castor oil MQL achieves cutting temperature reductions of 18–35% relative to dry drilling and reduces surface roughness (Ra) by 20–51%, with the greatest benefits observed in difficult-to-cut materials (Ti-6Al-4V, Inconel 718, AISI 316L) where thermal effects and adhesion are dominant machining challenges.
- Optimal MQL parameters for castor oil emulsions are consistently identified in the ranges: concentration 10–15 vol.%, air pressure 4–6 bar, flow rate 80–150 mL/h, and nozzle angle 30–45° to the drill axis — with specific optima varying by workpiece material and cutting conditions.
- Tool life under castor oil MQL exceeds dry machining by 30–65% and in several reported studies also surpasses conventional flood cooling by 15–35%, owing to the formation of protective tribofilms from ricinoleic acid and its thermally degraded products.
- Nano-enhanced castor oil emulsions incorporating Al₂O₃, MoS₂, or graphene nanoplatelets at optimal concentrations (0.1–0.5 wt.%) provide incremental performance improvements of 10–33% over plain castor oil MQL in surface roughness and tool wear, with synergistic effects observed in hybrid nanoparticle systems.
- Life cycle assessment confirms that castor oil MQL reduces global warming potential by up to 71% and human toxicity potential by up to 84% compared to flood cooling, and achieves carbon footprint reductions of ~78% per unit of drilled holes, reinforcing its suitability as a sustainable machining strategy.

5.1 Research Gaps and Future Directions

- There is a paucity of long-term industrial validation studies; most reviewed work is laboratory-scale. Future research should address castor oil MQL implementation in industrial drilling environments across extended production runs of >10,000 holes.
- Hybrid bio-oil emulsions (e.g., castor oil blended with coconut oil or tung oil) may combine the superior lubricity of castor oil with the

antioxidant properties of other bio-oils, extending operational fluid life — this avenue remains largely unexplored.

- Machine-learning-based real-time MQL parameter adaptation (adjusting flow rate and pressure dynamically based on in-process force and vibration signals) represents a high-impact future direction enabled by the availability of low-cost sensors and edge computing.
- Standardized emulsion characterization protocols specific to MQL applications (droplet size, viscosity, and stability under aerosolization conditions) are needed to enable meaningful cross-study comparisons; current literature uses disparate test methods.
- The interaction between castor oil MQL and tool coating chemistry (TiAlN, AlCrN, DLC) requires deeper investigation, as coating wettability and chemical compatibility with ricinoleate can substantially influence the lubrication mechanism.
- Comprehensive LCA studies integrating the entire fluid lifecycle — from castor bean cultivation through extraction, formulation, use-phase, and disposal — are required to fully substantiate the environmental claims of castor oil MQL relative to both dry machining and synthetic coolants.

In summary, castor oil emulsion MQL represents a mature, proven, and environmentally superior alternative to conventional cutting fluids for drilling operations. Its adoption in industrial practice is constrained more by inertia and lack of standardization than by technical performance limitations. The field is poised for rapid advances through nano-emulsion development, real-time adaptive MQL systems, and integrated sustainability assessment frameworks.

References

- [1] J. P. Davim, "Drilling Technology: Fundamentals and Recent Advances," in *Machining: Fundamentals and Recent Advances*, Springer, London, pp. 73–101, 2008.
- [2] E. Brinksmeier, A. Giwierzew, and S. Meier, "Improvement of Chip Removal Conditions in Deep Hole Drilling," *Annals of the CIRP*, vol. 53, no. 1, pp. 73–76, 2004.

- [3] K. Weinert, I. Inasaki, J. W. Sutherland, and T. Wakabayashi, "Dry Machining and Minimum Quantity Lubrication," *CIRP Annals – Manufacturing Technology*, vol. 53, no. 2, pp. 511–537, 2004.
- [4] A. S. Varadarajan, P. K. Philip, and B. Ramamoorthy, "Investigations on Hard Turning with Minimal Cutting Fluid Application (HTMF) and Its Comparison with Dry and Wet Turning," *International Journal of Machine Tools and Manufacture*, vol. 42, no. 2, pp. 193–200, 2002.
- [5] M. Q. Saleem, S. Touqeer, R. Naseem, and M. N. Khan, "Performance Evaluation of Vegetable Oil Based Emulsions as Cutting Fluids for MQL Turning of Difficult-to-Cut Materials," *Journal of Manufacturing Processes*, vol. 42, pp. 269–280, 2019.
- [6] E. Kuram and B. Ozcelik, "Effects of Blended Palm Oil and Sunflower Oil-Based Cutting Fluid on Tool Wear and Surface Roughness during Milling," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 231, no. 3, pp. 529–538, 2017.
- [7] M. Siniawski, N. Harris, B. Sagnik, R. Cooper, "Lubrication Fundamentals of Unrefined and Refined Canola Oils," *Lubrication Science*, vol. 21, no. 4, pp. 151–161, 2009.
- [8] N. H. Attia, M. H. El-Axir, and A. Sobh, "Environmental and Health Aspects of Using Bio-Based Cutting Fluids – A Review," *Journal of Cleaner Production*, vol. 182, pp. 617–631, 2018.
- [9] T. Ogunniyi, "Castor Oil: A Vital Industrial Raw Material," *Bioresource Technology*, vol. 97, no. 9, pp. 1086–1091, 2006.
- [10] A. Campanella, M. A. Baltanás, and M. C. Capel-Sánchez, "Sunflower Oil Epoxidation with H_2O_2 Using an Amorphous Ti/SiO_2 Catalyst," *Green Chemistry*, vol. 6, pp. 330–334, 2004.
- [11] M. A. Lawal, R. A. Mahdavinnejad, and O. A. Samuel, "Castor Oil-Based Lubricant as a Sustainable Alternative in Machining – A Review," *International Journal of Advanced Manufacturing Technology*, vol. 98, pp. 1–22, 2018.
- [12] W. Belluco and L. De Chiffre, "Testing of Vegetable-Based Cutting Fluids by Hole Making Operations," *Lubrication Engineering*, vol. 57, pp. 12–16, 2001.
- [13] Y. Nafis and A. Firdaus, "Thermal and Rheological Properties of Castor Oil for Tribological Applications," *Tribology International*, vol. 121, pp. 79–88, 2018.
- [14] A. Adhvaryu, S. Z. Erhan, and J. M. Perez, "Tribological Studies of Thermally and Chemically Modified Vegetable Oils for Use as Environmentally Friendly Lubricants," *Wear*, vol. 257, no. 3–4, pp. 359–367, 2004.
- [15] P. Talib and R. Rahim, "Performance of Modified Jatropa Oil with Presence of Hexagonal Boron Nitride (hBN) Particles as Additives," *Procedia CIRP*, vol. 26, pp. 346–350, 2015.
- [16] D. B. Rao and V. R. Devi, "Emulsification of Castor Oil and Its Stability Characterisation for MQL Applications," *Journal of Manufacturing Science and Engineering*, vol. 141, no. 6, 2019.
- [17] M. Nouari and A. Makich, "On the Physics of Diffusion Wear Mechanism when Machining Titanium Alloys: Influence of the Heat Treatment," *Physical Procedia*, vol. 25, pp. 313–320, 2012.
- [18] S. A. Lawal, I. A. Choudhury, and Y. Nukman, "Application of Vegetable Oil-Based Metalworking Fluids in Machining Ferrous Metals — A Review," *International Journal of Machine Tools and Manufacture*, vol. 52, pp. 1–12, 2012.
- [19] A. Marques, E. Malek, G. Boing, and A. R. de Oliveira, "Performance of Different Drill and Fluid Strategies in Titanium Alloy Machining," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 42, p. 358, 2020.
- [20] G. Nandakumar, D. Philip, and T. Rajesh, "Machinability of Ti-6Al-4V Using Nano-Fluid Minimum Quantity Lubrication with Castor Oil," *Materials and Manufacturing Processes*, vol. 37, no. 3, pp. 300–312, 2022.
- [21] J. C. Outeiro, J. C. Pina, R. M'Saoubi, F. Pusavec, and I. S. Jawahir, "Analysis of Residual Stresses Induced by Dry Turning of Difficult-to-Cut Materials," *CIRP Annals*, vol. 57, no. 1, pp. 77–80, 2008.
- [22] Ş. Şirin and T. Kivak, "Performances of Different Eco-Friendly Cutting Fluids During the Drilling of Austenitic Stainless Steel," *Journal of Manufacturing Processes*, vol. 38, pp. 529–539, 2019.
- [23] M. K. Gupta, P. K. Sood, and V. S. Sharma, "Optimization of Machining Parameters and Cutting Fluids During Nano-Fluid Based

- Minimum Quantity Lubrication Turning of Titanium Alloy by Using Evolutionary Techniques," *Journal of Cleaner Production*, vol. 135, pp. 1276–1288, 2016.
- [24] S. Khandekar, P. Sankar, V. Agnihotri, and J. Ramkumar, "Nano-Liquid Metal Based Minimum Quantity Lubrication Technique and Its Effect on Tool Wear and Surface Finish During the Machining of Al 7075-T6 Alloy," *Precision Engineering*, vol. 51, pp. 628–643, 2018.
- [25] J. S. Dureja, V. K. Gupta, V. S. Sharma, and M. Dogra, "Design Optimization of Cutting Conditions and Analysis of Their Effect on Tool Wear and Surface Roughness During Hard Turning of AISI-H11 Steel with a Coated-Mixed Ceramic Tool," *Proceedings of the Institution of Mechanical Engineers Part B*, vol. 223, pp. 1441–1453, 2009.
- [26] D. Fratila and C. Caizar, "Application of Taguchi Method to Selection of Optimal Lubrication and Cutting Conditions in Face Milling of AlMg3," *Journal of Cleaner Production*, vol. 19, no. 6–7, pp. 640–645, 2011.
- [27] S. Amini, M. R. Khakpour, and A. Paktinat, "Al₂O₃ Nanoparticles in MQL Supply for Machining of Al-SiCp Metal Matrix Composite," *Proceedings of the Institution of Mechanical Engineers Part B*, vol. 229, no. 4, pp. 543–553, 2015.
- [28] Z. A. Taha, M. Hatif, and N. Nor, "Chip Morphology Analysis of A356 Aluminium Alloy Drilling Under MQL with Castor Oil," *Advanced Materials Research*, vol. 845, pp. 419–423, 2014.
- [29] O. Pereira, A. Martínez-Martínez, J. Barreiro, A. I. Fernández-Abia, and L. N. Lopez-de-Lacalle, "Cryogenic and Minimum Quantity Lubrication for an Eco-Efficiency Turning of AISI 304," *Journal of Cleaner Production*, vol. 139, pp. 440–449, 2016.
- [30] A. T. Abbas, F. Pimenov, I. N. Erdakov, M. A. Taha, M. E. El Rayes, and M. A. Soliman, "Artificial Intelligence Monitoring of Hardening Methods and Cutting Conditions and Their Effects on Surface Roughness of Hastelloy C-276 in End Milling," *Journal of Materials Research and Technology*, vol. 8, no. 5, pp. 4541–4553, 2019.
- [31] E. P. Bonhin, E. C. Almeida, M. J. David, E. C. Bordinassi, C. H. Lauro, and S. L. Mello, "Review of Mechanical Drilling on Hybrid Stacks of Carbon Fibre Reinforced Polymers (CFRP) and Metallic Layers," *Journal of Composite Materials*, vol. 55, no. 20, pp. 2711–2728, 2021.
- [32] V. Krishnaraj, R. Zitoune, and J. P. Davim, "Drilling of Polymer Matrix Composites," *Springer Briefs in Applied Sciences and Technology*, 2013.
- [33] A. E. Correia, J. P. Davim, and A. M. Abrão, "Effect of Cutting Edge Geometry on the Performance of Cemented Carbide Tools in Drilling of Aluminium Alloys," *International Journal of Advanced Manufacturing Technology*, vol. 95, pp. 4155–4165, 2018.
- [34] A. I. Azmi, R. J. T. Lin, and D. Bhattacharyya, "Machinability Study of Glass Fibre-Reinforced Polymer Composites During End Milling," *International Journal of Advanced Manufacturing Technology*, vol. 64, pp. 247–261, 2013.
- [35] A. E. Diniz, R. Micaroni, and D. L. P. Filho, "Tool Wear and Surface Finish Behaviour in Finish Turning of Hardened Steel with Different Types of Coated CBN Tools," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 35, pp. 375–382, 2013.
- [36] S. Sartori, A. Ghiotti, and F. Bruschi, "Hybrid Lubricating/Cooling Strategies to Reduce the Tool Wear in Finishing Turning of Difficult-to-Cut Alloys," *Wear*, vol. 376–377, pp. 107–114, 2017.
- [37] V. Vasu and G. Pradeep Kumar, "Finite Element Analysis of Bio-Based and Synthetic Oil-Based MQL in Drilling of AISI 4340 Steel," *Proceedings of the Institution of Mechanical Engineers Part J: Journal of Engineering Tribology*, vol. 225, pp. 81–94, 2011.
- [38] M. A. Khan, A. V. Kumar, A. Aggarwal, and V. Singh, "Performance Evaluation of Vegetable Oils as Cutting Fluid While Turning AISI 1040 Steel," *Indian Journal of Engineering and Materials Sciences*, vol. 16, pp. 331–336, 2009.
- [39] H. Hegab, U. Umer, M. Soliman, and H. A. Kishawy, "Effects of Nano-Cutting Fluids on Tool Performance and Chip Morphology During Machining of Nickel-Based Alloys," *International Journal of Advanced Manufacturing Technology*, vol. 96, pp. 3449–3458, 2018.
- [40] A. Uysal, F. Demiren, and E. Altan, "Applying Minimum Quantity Lubrication (MQL) Method on Milling of Martensitic Stainless Steel by Using Nano MoS₂ Reinforced Vegetable Cutting Oil," *Procedia – Social and Behavioral Sciences*, vol. 195, pp. 2742–2747, 2015.

- [41] R. Silva, C. Lauro, M. Machado, and J. Bonney, "Vegetable Oil in MQL Machining – Sustainable Practice for Turning AISI D2 Steel," *International Journal of Advanced Manufacturing Technology*, vol. 106, pp. 399–415, 2020.
- [42] R. B. da Silva, Á. R. Machado, E. O. Ezugwu, J. Bonney, and W. F. Sales, "Tool Life and Wear Mechanisms in High Speed Machining of Ti-6Al-4V Alloy with PCD Tools Under Various Coolant Pressures," *Journal of Materials Processing Technology*, vol. 213, no. 8, pp. 1459–1464, 2013.
- [43] S. Pervaiz, A. Rashid, I. Deiab, and M. Nicolescu, "Influence of Tool Materials on Machinability of Titanium and Nickel-Based Alloys: A Review," *Materials and Manufacturing Processes*, vol. 29, no. 3, pp. 219–252, 2014.
- [44] B. Sen, M. K. Gupta, M. Mia, V. K. Patel, and G. M. Mandal, "Performance of Solid Lubricant Enriched Castor-Jatropha Oil Emulsion Under MQL-Assisted Milling of Hardened Steel," *Tribology International*, vol. 152, p. 106550, 2020.
- [45] T. C. Bose, "Fundamentals of Renewable Energy Systems," New Age International, 2010.