International Journal of Research in Engineering and Innovation Vol-10, Issue-3 (2026), 115-129

IJREI

International Journal of Research in Engineering and Innovation (IJREI)

Journal home page: https://ijrei.com/

RESEARCH PAPER

Development and characterization of eco-friendly cutting fluid for CNC Turning of AISI D3 steel using CBN and PCBN tools

H Ramamurthy Naik, Radhey Shyam Mishra, Ranganath M.S.

Department, of Mechanical , Production Industrial and Automobiles Engineering, Delhi Technological University Delhi, India

Article Information

Received: 18 March 2026
Revised: 09 June 2026
Accepted: 18 June 2026
Available online: 20 June 2026

Keywords:

Computer Numerical Control
Cubic Boron Nitride
Polycrystalline Cubic Boron Nitride
Turning
Grinding
Milling

Abstract

This study investigates the development of an eco-friendly cutting fluid and evaluates its rheological and tribological properties for CNC machining of AISI D3 steel using CBN and PCBN tools. AISI D3, known for its high hardness and wear resistance, poses challenges in machining, particularly in achieving optimal surface finish and minimizing tool wear. Traditional cutting fluids often involve environmental and health hazards, motivating the need for sustainable alternatives. The research focuses on formulating a biodegradable cutting fluid with superior lubricating and cooling properties. Comprehensive rheological tests are conducted to characterize viscosity, flow behaviour, and thermal stability, while tribological evaluations assess friction reduction and wear resistance. CNC machining trials validate the performance of the developed fluid by analysing surface roughness, tool wear, and cutting forces. The results demonstrate that the eco-friendly cutting fluid significantly enhances turning performance, reduces frictional heat, and extends tool life while maintaining environmental sustainability. This work contributes toward sustainable precision turning applications.

1. Introduction

Turning of hardened tool steels is a critical operation in modern manufacturing industries, particularly in applications such as dies, moulds, and precision components. Among these materials, AISI D3 tool steel is widely used due to its high carbon and chromium content, which imparts excellent hardness, wear resistance, and dimensional stability. However, these same properties make it extremely difficult to machine, especially under conventional cutting conditions [1]. Hard turning of AISI D3 (typically in the range of 55-62 HRC) involves severe tribological interactions at the tool-chip interface, leading to high cutting forces, elevated temperatures, rapid tool wear, and potential deterioration of surface integrity [2]. Turning, grinding, milling, drilling, and other machining operations use this most common cooling method. Fig. 1 shows the setup of the wet cooling process. This cooling procedure supplies cutting fluid continuously to the cutting zone. This method uses more cutting or lubricating fluid than any other cooling and lubrication method. This process uses 20 lit/min cutting fluid [3]. This cooling approach is disadvantageous since operators who are always in contact with this lubricant have about 80% illness [4]. Due to its high cost, operator danger, and environmental contamination from disposal concerns, this technology is no longer used, and everyone is looking for an alternative. To overcome these challenges, advanced cutting tools such as cubic boron nitride (CBN) and polycrystalline cubic boron nitride (PCBN) have been widely adopted due to their superior hardness, thermal stability, and resistance to wear. These tools are capable of replacing grinding operations in many applications, offering improved productivity and flexibility. However, even with these advanced tool materials, turning performance is strongly influenced by the tribological and thermal conditions at the cutting zone, which are governed significantly by the type and effectiveness of cutting fluid employed [5]. Traditionally,

Corresponding author: R. S. Mishra
Email Address: rsmishra@dtu.ac.in
https://doi.org/10.36037/IJREI.2026.10305

mineral oil-based cutting fluids have been extensively used to reduce friction, dissipate heat, and improve surface finish. These fluids function by providing lubrication at the tool-chip interface and cooling the cutting zone. Despite their effectiveness, conventional cutting fluids pose serious environmental and health concerns, including toxic emissions, skin irritation, and difficulties in disposal and recycling. Furthermore, stringent environmental regulations and rising awareness of sustainable manufacturing have driven the need to develop eco-friendly alternatives [6].

Figure 1: Setup of wet turning

In this context, green cutting fluids, particularly those derived from vegetable oils, have emerged as promising substitutes for conventional fluids. Vegetable oils possess inherent advantages such as biodegradability, renewability, and low toxicity. More importantly, their chemical structure characterized by long-chain fatty acids and polar ester groups enables strong adsorption onto metal surfaces, forming a stable lubricating film that reduces friction and wear [7]. This boundary lubrication mechanism is especially beneficial in hard turning, where extreme contact pressures and temperatures prevail.

Recent studies have demonstrated that vegetable oil-based cutting fluids can significantly improve turning performance by reducing cutting forces, tool wear, and surface roughness. For instance, Dhar et al. reported that the use of biodegradable oils in turning resulted in enhanced lubrication and extended tool life compared to dry and conventional wet turning [6]. Similarly, Lawal et al. highlighted the superior tribological properties of vegetable oils, attributing their performance to high viscosity index and excellent lubricity [7]. However, these fluids also present certain limitations, including oxidation instability, limited thermal conductivity, and susceptibility to degradation at high temperatures, which can restrict their performance under severe turning conditions.

To address these limitations, it is essential to conduct a comprehensive characterization of green cutting fluids, particularly focusing on their rheological and tribological properties. Rheological characterization provides insights into the fluid's viscosity, flow behaviour, and temperature-dependent stability, which directly influence its ability to penetrate the cutting zone and form a lubricating film. Tribological characterization, on the other hand, evaluates friction, wear, and lubrication mechanisms under simulated contact conditions, typically using a pin-on-disc tribometer. These studies are crucial for understanding the fluid's performance under real turning environments.

Despite the growing body of research, there remains a lack of systematic studies that integrate fluid formulation, rheological analysis, tribological evaluation, and actual turning performance, particularly for hard turning of AISI D3 steel using advanced cutting tools such as CBN and PCBN. Furthermore, most existing studies focus on either tribological testing or turning performance independently, without establishing a direct correlation between fluid properties and turning outcomes. Therefore, the present study aims to develop a biodegradable eco-friendly cutting fluid and evaluate its performance through a comprehensive approach involving rheological characterization, tribological testing, and CNC turning experiments. The turning performance is assessed in terms of cutting forces, surface roughness, and tool wear, while the environmental sustainability of the fluid is also considered. By establishing a link between fluid properties and turning behavior, this research provides valuable insights into the design and application of green cutting fluids for sustainable manufacturing.

2. Materials and Methods

2.1 Workpiece Material

The workpiece material selected for this study was AISI D3 cold-work tool steel, widely used in die and mould applications due to its high wear resistance and hardness. The material was heat-treated to achieve a hardness of 58 ± 2 HRC. The chemical composition of AISI D3 steel is presented in Table 1.

Table 1: Chemical Composition of AISI D3 Steel (wt%)

C	Cr	Mn	Si	Fe
2.0–2.3	11–13	0.6	0.6	Balance

Cylindrical specimens of dimensions Ø50 mm × 150 mm length were prepared and ground to ensure uniform surface conditions before machining.

2.2 Cutting Tool and Tool Holder

The inserts used in this study were of negative rake geometry, which is preferred in hard turning because it provides higher edge strength and better resistance to chipping under intermittent or high-load cutting conditions. [1] A commonly adopted insert configuration such as CNMG-type geometry was considered suitable for the present work because of its mechanical robustness and wide industrial acceptance in CNC turning operations shown in fig.2. The insert geometry consisted of a nose radius of 0.8 mm, clearance angle of 0° or 7° depending on insert style, and a strong cutting edge preparation to withstand the elevated stresses generated during machining of hardened steel. The nose radius was selected to obtain a balance between surface finish and cutting force generation [2].

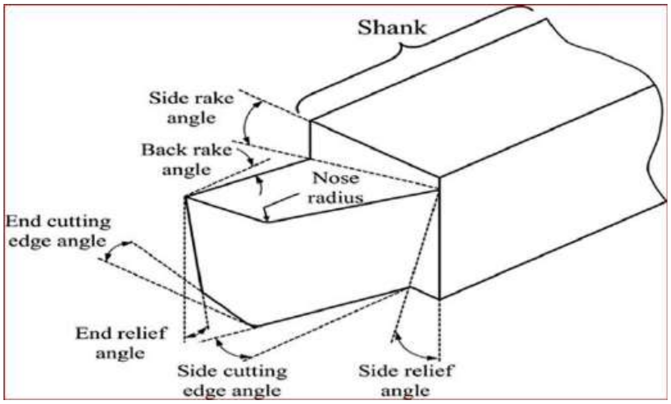

Figure 2: CNC Tool Geometry for CNC Turning Machine

In the present investigation, machining trials were carried out on a CNC turning centre using cubic boron nitride (CBN) and polycrystalline cubic boron nitride (PCBN) cutting inserts, in the tool holder and process of machining is shown in Fig. 3. 2.2. for hard turning of AISI D3 steel. Since AISI D3 is high-carbon, high-chromium cold-work tool steel with high hardness and strong abrasion resistance, conventional carbide tools are generally inadequate under severe cutting conditions. Therefore, CBN and PCBN tools were selected to ensure dimensional accuracy, thermal stability, and prolonged tool life during machining [3].Two types of cutting tools were used: Cubic Boron Nitride (CBN) inserts and Polycrystalline Cubic Boron Nitride (PCBN) inserts. The selection of CBN and PCBN inserts with a rigid tool holder was therefore considered appropriate for the hard turning of AISI D3 steel, as this combination provides the necessary mechanical strength, thermal resistance, and process stability to evaluate the performance of the developed eco-friendly cutting fluid under controlled machining conditions. Cutting Tool and Tool Holder Specifications are shown in Table 2 [4].

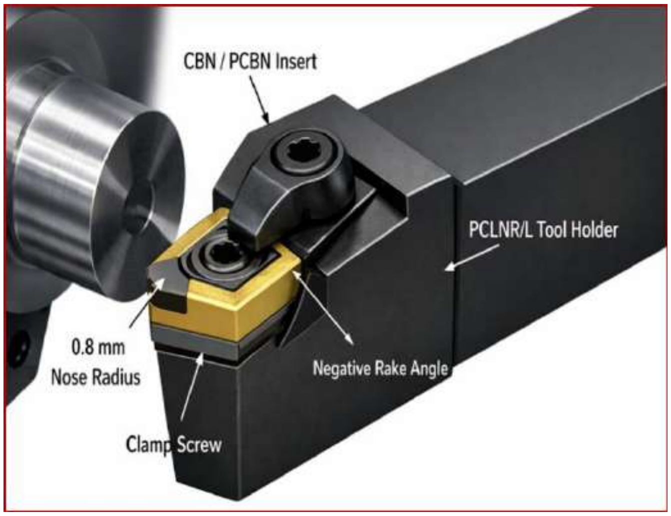

Figure 3: Cutting Tool & Tool Holder of the CNC machine

Table 2: Cutting Tool and Tool Holder Specifications

S. No.	Parameter	Specification
1.	Cutting tool material	CBN and PCBN
2.	Nose radius	0.8 mm
3.	Insert geometry	Negative rake
4.	Tool holder type	PCLNR / external turning holder
5.	Clamping method	Mechanical clamp with screw
6.	Tool holder material	Hardened alloy steel
7.	Application	Hard turning of AISI D3 steel

2.3 Tribological Testing

Tribological performance was evaluated using a pin-on-disc tribometer in accordance with ASTM G99 standard. The Fig. 4 presents the experimental arrangement employed to evaluate the tribological behaviour of materials under controlled wet lubrication conditions using a pin-on-disc tribometer. The disc specimen, made of AISI D3 steel (≈58 ± 2 HRC), is mounted on a motor-driven spindle and rotates at a predefined speed to simulate sliding contact conditions. A stationary test pin, fabricated from CBN/PCBN material, is held vertically against the rotating disc under a constant normal load, ensuring consistent contact pressure throughout the experiment [1, 2].

A coolant delivery system is integrated into the setup, where the cutting biodegradable fluid (mineral oil or eco-friendly vegetable oil-based fluid) is supplied directly to the pin–disc interface through a nozzle. This arrangement facilitates simultaneous lubrication and cooling, leading to the formation of a thin lubricating film at the contact zone, which reduces friction, wear, and temperature rise during sliding [3], [4]. The excess fluid is collected in a coolant collection tray, maintaining a clean and controlled testing environment.

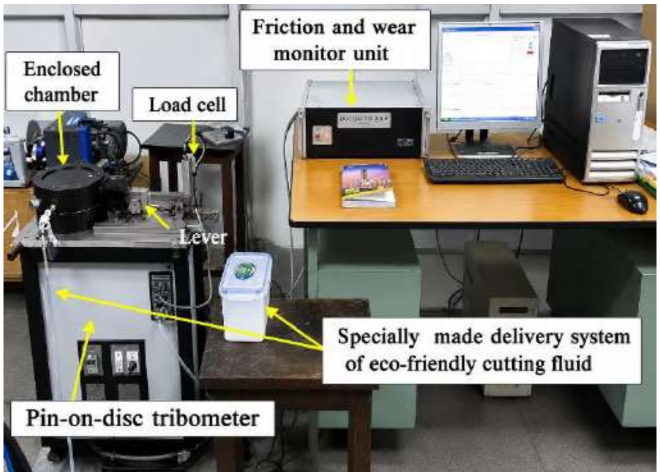

Figure 4: Tribological performance evaluation using a pin-on-disc tribometer in accordance with ASTM G99.

The contact region between the pin and disc, highlighted in the inset, illustrates the tribological interaction where frictional heat is generated and dissipated by the applied coolant. The presence of the lubricating film minimizes direct metal-to-metal contact, thereby reducing adhesive and abrasive wear mechanisms [5, 6]. Overall, the Fig. 5a, b pin and disc that were used in experiments. The pin was used as the CBN Tip material ans disc was used as the work piece material which were demonstrates a comprehensive experimental setup that integrates material testing, lubrication, and measurement systems, enabling systematic evaluation of friction, wear behaviour, and lubrication efficiency of cutting fluids under standardized ASTM G99 conditions [7].

Table .3 shows the operating conditions used in the pin-on-disc wear experiment. The applied load was varied from 10 to 30 N to analyze the effect of contact pressure on wear and friction behaviour. The sliding speed ranged from 0.5 to 1.5 m/s to study the influence of relative motion and frictional heating during sliding. A constant sliding distance of 1000 m was maintained to obtain stable and measurable wear characteristics. The tests were performed under both dry and eco-friendly lubricated conditions to compare the tribological performance of the material in the absence and presence of sustainable lubrication. The pin on disc experiment test conditions are shown in Table 3.

Table 3: Test Conditions for the pin on disc experiment setup

Parameter	Value
Load	10–30 N
Sliding speed	0.5–1.5 m/s
Sliding distance	1000 m
Environment	Dry and eco-friendly lubricated

The coefficient of friction (μ) was calculated as:

$$\mu = \frac{F}{N} \quad (1)$$

where: *F* = frictional force (N), *N* = normal load (N).

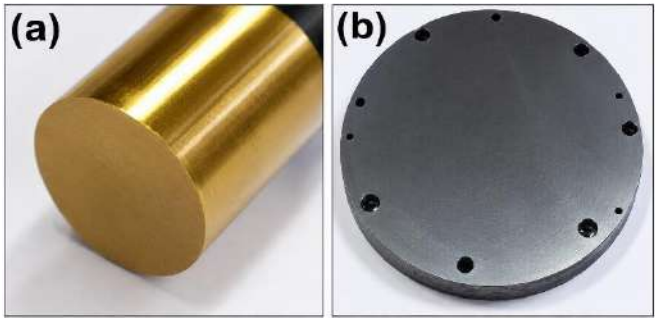

Figure 5: (a) CBN/PCBN material pin and (b) AISI D3 disc

2.4 Wear Measurement

Wear was quantified by measuring weight loss using a precision balance and by analyzing wear scars using optical microscopy. Wear behaviour of the tool and material surfaces was evaluated through both tribological testing (pin-on-disc) and machining experiments to obtain a comprehensive understanding of wear mechanisms under wet cooling conditions. Wear tests were conducted using a pin-on-disc tribometer in accordance with ASTM G99 standard. The AISI D3 steel disc acted as the counter face, while the CBN/PCBN pin served as the test specimen. During testing, a constant normal load was applied, and the disc was rotated at a controlled speed under wet lubrication conditions. The wear of the pin specimen was quantified using the weight loss method. The initial and final weights of the pin were measured using a precision electronic balance with an accuracy of ±0.1 mg [8]. The wear volume was calculated using by the equation (2).

$$V = \frac{\Delta W}{\rho} \quad (2)$$

Where: V = wear volume (mm^3), ΔW = weight loss (g), ρ = density of the pin material (g/mm^3).

Now the specific wear rate (K) was determined using equation (3)

$$K = \frac{V}{N \cdot L} \quad (3)$$

where: *K* = specific wear rate ($mm^3/N{\cdot}m$), *N* = applied load (N), and *L* = sliding distance (m).

Post-test analysis of the wear track on the disc and the worn pin surface was carried out using an optical microscope and SEM to identify wear mechanisms such as adhesive wear, abrasive wear, and tribofilm formation.

2.4.1 Tool Wear Measurement in CNC Turning

Tool wear during CNC turning experiments was evaluated in accordance with ISO 3685 standard, which specifies tool life testing procedures for single-point cutting tools.

The primary wear parameter measured was flank wear (VB), which is the average width of the wear land formed on the tool flank face. Flank wear was measured using an optical toolmaker's microscope with micrometre resolution. Tool wear progression was monitored at regular machining intervals. The tool was considered to have reached the end of its useful life when: *VBmax≥0.3 mm* as per ISO recommendations [3]. In addition to flank wear, crater wear (KT) and edge chipping were also examined using SEM analysis to understand wear mechanisms under different lubrication conditions.

2.4.2 Surface Wear and Roughness Analysis

The wear behaviour of the machined surface was indirectly evaluated through surface roughness measurements (Ra) using a contact profilometer in accordance with ISO 4287 standard. Increased surface roughness is often associated with higher tool wear and unstable cutting conditions. The theoretical surface roughness was estimated using equation (4)

$$R_a = \frac{f^2}{32r} \quad (4)$$

Where: ***f*** = feed rate (mm/rev), ***r*** = tool nose radius (mm)

2.4.3 Wear Mechanisms under Wet Cooling

Under wet cooling conditions, the presence of a cutting fluid leads to the formation of a lubricating tribofilm at the tool–workpiece interface. This reduces direct asperity contact and minimizes wear. The dominant wear mechanisms observed include: (i)Adhesive wear reduction due to lubrication. (ii) Abrasive wear suppression due to reduced friction. (iii)

Oxidative wear control due to the cooling effect.

Eco-friendly cutting fluids, particularly vegetable oil-based fluids, enhance wear resistance due to their strong polar adsorption and film-forming capability [4, 5]. The Summary of Wear Measurement Approach is given in Table 4.

Table 4: Summary of Wear Measurement Approach

Method	Parameter Measured	Standard
Pin-on-disc	Wear volume, friction	ASTM G99
CNC turning	Flank wear (VB), crater wear	ISO 3685
Surface analysis	Roughness (Ra)	ISO 4287
Microscopy	Wear mechanisms	SEM

2.5 Development of Eco-Friendly Cutting Fluid

Environmentally friendly cutting fluids have grown in popularity since mineral-oil-based fluids cause disposal, toxicity, and occupational-health issues and increase manufacturing costs it process shows in fig.6. For sustainable machining, mineral oils are being replaced by biodegradable, vegetable-oil-based cutting fluids [1].

The literature emphasizes vegetable oils as green cutting fluid base stocks. Renewability, biodegradability, high lubricity, and strong polarity make vegetable oils suitable for forming stable boundary layers on metallic surfaces, according to 2021 and 2024 reviews. Because these films prevent direct asperity contact at tool–chip and tool–work interfaces, vegetable-oil-based cutting fluids are intensively investigated for turning, milling, drilling, and grinding [2].

The research reveals that developing eco-friendly cutting fluids involves more than using a vegetable oil. Researchers combine a basic oil with emulsifiers, antioxidants, anti-wear chemicals, and performance enhancers like boric acid or nanoparticles to make these fluids. A 2022 study on machining AISI 1010 steel developed a neem-seed-oil-based cutting fluid with high biodegradability, reduced cutting force, flank wear, and good flash/fire point, showing how formulation design affects machining performance and environmental behaviour [3].

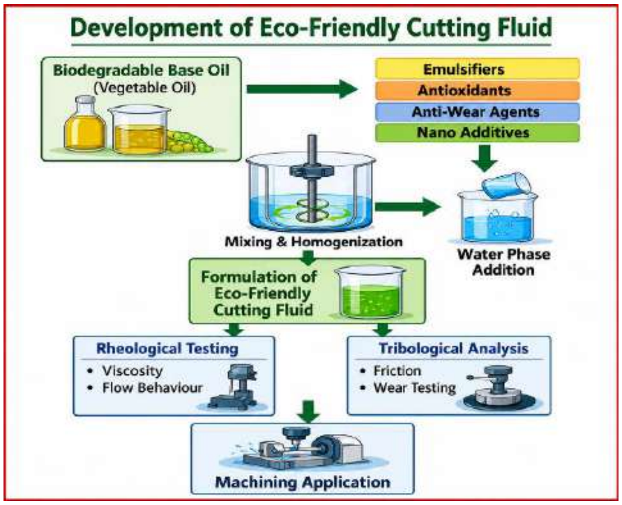

Figure 6: Schematic diagram for developing the eco-friendly cutting fluids

Rheological and thermophysical characterisation of green cutting fluids is another major area of research. Recent evaluations emphasize that viscosity, oxidation stability, and thermal behavior determine whether a fluid can penetrate the cutting zone, retain a lubricating coating, and remain stable at machining temperatures. The 2024 comprehensive analysis on vegetable-oil cutting fluids states that chemical modification can increase frictional performance and machining outcomes [4]. The biodegradable cutting fluid review emphasises viscosity and oxidation performance.

Many researches employ chemical modification to increase vegetable oil performance due to weak oxidation stability and heat resilience. Recently, transesterification, esterification, and epoxidation have been shown to improve anti-oxidation behavior and commercial application. The carboxyl group or fatty-acid chain structure can be modified to stabilize the fluid under severe machining conditions [4]. Use of nano-additives is another key development route. Recent evaluations show that mending, polishing, and rolling at the contact interface can increase machining performance with particles like alumina, silica, molybdenum disulfide, graphene, and hexagonal boron nitride. Nano-enhanced vegetable-oil cutting fluids improve friction reduction, temperature management, tool life, and surface polish compared to unmodified vegetable oils, according to 2024 and 2025 literature [4]. The literature also reveals that eco-friendly cutting fluid development is increasingly connected to MQL and near-dry machining. The 2024 comprehensive review found that vegetable-oil-based cutting fluids can reduce surface roughness compared to dry and flood machining when used with MQL, while the 2021 review found that vegetable oils can replace synthetic cutting fluids in many sustainable machining situations. This is crucial since modern development involves fluid chemistry and delivery strategy [2]. The literature is scarcer for hard turning and tool-steel machining than for mild and stainless steel turning, but the tendency is obvious. Recent reviews demonstrate that vegetable-oil-based fluids improve surface quality, friction, and wear compared to dry cutting and some water- or mineral-oil systems. Advanced lubricants and hybrid nano-fluids are being used to optimise turning performance on toughened and AISI D-series steels [5]. The literature suggests that eco-friendly cutting fluid development has progressed through four stages: selection of biodegradable base oils, formulation with additives and emulsifiers, chemical modification to improve oxidation stability, and nano-enhancement to improve tribological and thermal behavior. Recent reviews agree that vegetable-oil-based cutting fluids can outperform conventional fluids in lubrication-dominated machining, but their widespread industrial adoption depends on oxidation resistance, long-term stability, and process-specific optimization [2]. The eco-friendly cutting fluid was formulated with a vegetable oil base (palm/soybean oil) and biodegradable additives. The composition is Vegetable oil 70%, Emulsifier is 15%, Anti-oxidant additive is 5%, and Distilled water is 10%. The formulation was homogenized using a mechanical stirrer at 1500 rpm for 30 minutes to ensure uniform dispersion.

2.6 Rheological Characterization of Eco-Friendly Cutting

Fluid

Rheological characterization of the developed eco-friendly cutting fluid was carried out to evaluate its flow behaviour, viscosity variation, and thermal stability, which are critical parameters influencing lubrication and cooling performance during machining. The rheological properties determine the ability of the fluid to penetrate the cutting zone, form a stable lubricating film, and dissipate heat effectively [1, 2].

2.6.1 Viscosity Measurement

Viscosity is a key parameter governing the lubrication performance of cutting fluids. It influences the formation of a lubricating film at the tool–chip interface and affects the fluid's ability to reduce friction and wear. The viscosity of the developed fluid was measured using a rotational viscometer over a temperature range of 25°C to 80°C. The relationship between shear stress and shear rate is expressed by equation (5)

$$\tau=\mu\cdot\gamma \qquad (5)$$

where:τ= shear stress (Pa), μ = dynamic viscosity (Pa·s), and $\dot{\gamma}$ = shear rate (s^{-1}).
The results indicated that viscosity decreases with increasing temperature, which is typical behaviour for vegetable oil-based fluids due to reduced intermolecular forces at elevated temperatures [3].

2.6.2 Flow Behaviour

The flow behaviour of the cutting fluid was analysed to determine whether it exhibits Newtonian or non-Newtonian characteristics. The developed eco-friendly cutting fluid showed pseudo-plastic (shear-thinning) behaviour, where viscosity decreases with increasing shear rate.
This behaviour is advantageous in machining applications because: At low shear rates → higher viscosity ensures effective lubrication. And at high shear rates → lower viscosity improves fluid flow and heat dissipation. Such behaviour enhances the fluid's adaptability under varying machining conditions [4].

2.6.3 Temperature–Viscosity Relationship

The temperature dependence of viscosity was evaluated to assess the thermal stability of the fluid. The relationship can be described using an Arrhenius-type equation (6)

$$\mu=A\,.e^{E/RT} \qquad (6)$$

where: μ = viscosity (Pa·s), A = pre-exponential constant, E= activation energy for flow, R = universal gas constant, and T = absolute temperature (K).
The developed fluid maintained stable viscosity within the tested temperature range, indicating good thermal performance under machining conditions.

2.6.4 Rheological Significance in Machining

The rheological properties directly influence machining performance in the following ways:
i. High viscosity → improved lubrication and reduced wear.
ii. Low viscosity at high temperature → better cooling and chip evacuation.
iii. Shear-thinning behaviour → adaptive lubrication under varying cutting speeds.

Vegetable oil-based cutting fluids exhibit superior lubricity due to their polar molecular structure, which enhances boundary lubrication [5].

The rheological characterisation confirms that the developed eco-friendly cutting fluid have Exhibits stable viscosity across the temperature range, shows beneficial pseudo-plastic behaviour, maintains lubrication efficiency under machining conditions and Supports effective cooling and friction reduction. The machining responses were evaluated through CNC turning experiments conducted on a CNC lathe machine under three different machining environments, namely dry machining, conventional wet machining using mineral oil, and machining with the developed eco-friendly cutting fluid. The machining experiments were carried out by varying the major cutting parameters, including cutting speed in the range of 80–180 m/min, feed rate from 0.05–0.15 mm/rev, and depth of cut between 0.5–1 mm. These parameters were selected to analyze the influence of machining conditions and lubrication environment on machining performance.
Cutting force measurements were performed using a piezoelectric dynamometer capable of recording the three major force components generated during turning operations. The measured force components included cutting force (Fc), feed force (Ff), and radial force (Fr). These force measurements provided valuable information regarding tool loading conditions, machining stability, and the effectiveness of lubrication during cutting.

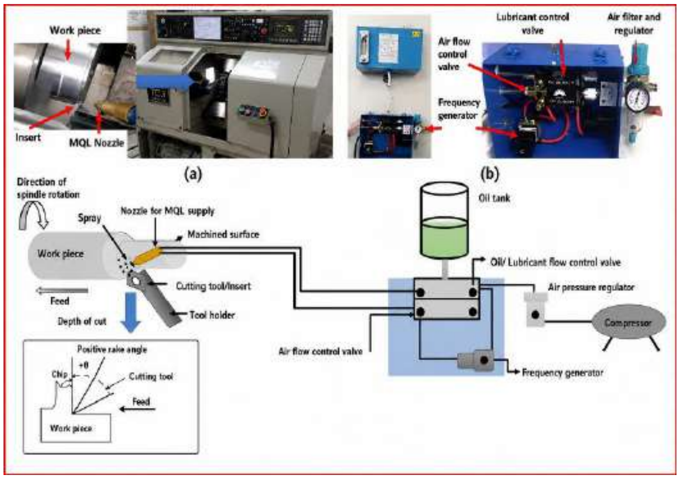

Figure 7: CNC Turning experimental setup

Tool wear analysis was conducted using both an optical microscope and a Scanning Electron Microscope (SEM) to examine the wear morphology and wear mechanisms developed on the cutting tool surface after machining. Flank wear (VB) was measured according to the ISO 3685 standard to evaluate tool life and wear progression under different machining environments. The detailed wear characterization enabled comparison of the tribological performance of dry machining, conventional cutting fluid, and the developed eco-friendly cutting fluid during CNC turning operations.

2.7 Experimental Design and Statistical Analysis

A Taguchi L9 orthogonal array was employed to design the experiments. Analysis of variance (ANOVA) was conducted to determine the significance of machining parameters on output *responses. Regression models were developed to predict machining performance:*

2.7.1 Taguchi L9 Orthogonal Array (OA) Design

The L9 array is ideal for investigating 3 factors at 3 levels each. This allows you to evaluate the main effects with only 9 experimental runs instead of the 27 required for a full factorial design. The proposed experimental matrix described by assuming in the research involves turning, common factors include Cutting Speed (v_c), Feed Rate (f), and Depth of Cut (a_p). The Design of the experiment is shown in Table 5.

Table 5: DOE structure

Exp. No	Factor Level			Performance Response (Y)
	Factor A (vc)	Factor B (f)	Factor C (ap)	
1	Level 1	Level 1	Level 1	Y_1
2	Level 1	Level 2	Level 2	Y_2
3	Level 1	Level 3	Level 3	Y_3
4	Level 2	Level 1	Level 2	Y_4
5	Level 2	Level 2	Level 3	Y_5
6	Level 2	Level 3	Level 1	Y_6
7	Level 3	Level 1	Level 3	Y_7
8	Level 3	Level 2	Level 1	Y_8
9	Level 3	Level 3	Level 2	Y_9

2.7.2 Signal-to-Noise (S/N) Ratio Analysis

Taguchi uses S/N ratios to measure the deviation of the quality characteristic from the desired value. Larger-is-Better (e.g., Tool Life) by equation (7):

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum\frac{1}{y^2}\right) \qquad (7)$$

Smaller-is-Better (e.g., Surface Roughness Ra, Cutting Force) by equation 8

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum y^2\right) \qquad (8)$$

Table 6 shows a typical ANOVA structure for a Taguchi L9 design analyzing machining parameters like speed, feed, and depth of cut (Doc) on responses such as surface roughness. Feed dominates with 65% contribution and a highly significant P-value, while error accounts for 10% unexplained variance.

Table 6: Sample ANOVA Table Structure

Source	DF	Seq SS	Adj MS	F-Value	P-Value	Contribution (%)
Speed	2	...	...	...	0.012	15
Feed	2	...	...	...	0.001	65
Doc	2	...	...	...	0.045	10
Error	2	...	...			10
Total	8	...				100

2.7.3 Regression modelling

To predict performance (Y) within the tested range, a Multiple Linear Regression Model is developed. A typical second-order model looks like shown in equation (9):

$$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_{12} AB + \beta_{13} AC + \cdots + \epsilon \qquad (9)$$

Where: β_0 is the constant, $\beta_{1,2,3}$ are linear coefficients., A, B, C are the coded or actual values of the machining parameters. The final step in your statistical analysis should be the Main Effects Plot and Interaction plot shows how the mean response changes as each factor moves from Level 1 to Level 3. Interaction Plot: Determines if the effect of one factor (e.g., Speed) depends on the level of another factor (e.g., Feed).

$$Y = f(V, f, d) \qquad (10)$$

where: Y represents output parameters such as surface roughness and tool wear. The environmental performance of the developed eco-friendly cutting fluid was evaluated to assess its suitability as a sustainable alternative to conventional mineral oil-based cutting fluids. The assessment focused on key parameters including biodegradability, toxicity, and environmental impact, following internationally recognized standards.

2.8 Biodegradability Test

Biodegradability of the developed cutting fluid was evaluated using the OECD 301F respirometric test method, which determines the extent of aerobic degradation of organic substances over a period of 28 days. The percentage biodegradation (D) was calculated using equation (11).

$$D(\%) = \frac{BOD}{ThOD} \times 100 \qquad (11)$$

where: BOD = Biochemical Oxygen Demand (mg/L) , ThOD = Theoretical Oxygen Demand (mg/L, A fluid is considered readily biodegradable if the degradation exceeds 60% within 28 days [1]

The eco-friendly cutting fluid developed in this study exhibited biodegradability greater than 60%, indicating its compliance with environmental standards and confirming its suitability for sustainable machining applications.

2.8.1 Toxicity Assessment

Toxicity of cutting fluids is a critical factor affecting both environmental and operator safety. Conventional mineral oils often contain harmful additives such as sulfur, chlorine, and heavy metals, which can lead to skin irritation, respiratory issues, and ecological damage [2]. In contrast, the developed eco-friendly cutting fluid was formulated using vegetable oil-based components, which are inherently non-toxic and biodegradable. The absence of hazardous additives significantly reduces health risks and improves workplace safety [3]. Biodegradability of the developed cutting fluid was evaluated using OECD 301F test method, where degradation above 60% within 28 days indicates environmentally acceptable performance.

2.8.2 Environmental Impact Analysis

The environmental impact of the cutting fluid was evaluated based on: (i) Renewability of raw materials (ii) Disposal and waste management requirements (iii) Carbon footprint reduction. Vegetable oil-based cutting fluids are derived from renewable resources and exhibit lower environmental impact compared to petroleum-based fluids. Additionally, their high biodegradability reduces the burden on waste treatment systems and minimizes soil and water contamination [4]. A comparative environmental assessment between conventional and eco-friendly cutting fluids is presented in Table 7.

Table 7: Environmental Comparison of Cutting Fluids

Parameter	Conventional Fluid	Eco-Friendly Fluid
Biodegradability	Low	High (>60%)
Toxicity	High	Low
Source	Petroleum-based	Renewable
Disposal	Complex	Easy
Environmental impact	High	Low

2.8.3 Sustainability Index

To quantify sustainability, a qualitative sustainability index (SI) was considered based on environmental parameters:

$$SI = f\,(B, T, E.) \tag{12}$$

where: B = Biodegradability, T = Toxicity, E = Environmental impact

The developed eco-friendly cutting fluid exhibited a higher sustainability index due to its superior biodegradability, low toxicity, and minimal environmental impact.

The environmental assessment confirms that the developed eco-friendly cutting fluid:

- Meets OECD biodegradability standards
- Exhibits low toxicity and improved operator safety
- Reduces environmental pollution
- Supports sustainable manufacturing practices

Thus, it can be considered a viable alternative to conventional cutting fluids in CNC machining applications.

3. Results and discussion

3.1 Tribological Performance Evaluation

Tribological performance was evaluated using a pin-on-disc tribometer in accordance with ASTM G99 to compare the behaviour of CBN and PCBN pins sliding against an AISI D3 steel disc under dry and eco-friendly lubrication conditions shown in Table 8. The tests were conducted at normal loads of 10, 20, and 30 N, while sliding speed and sliding distance were kept constant. The measured responses included coefficient of friction, weight loss, wear volume, and specific wear rate. The test Conditions are shown in Table 8.

Table 8: Experimental conditions for tribological testing

Parameter	Value
Standard	ASTM G99
Disc material	AISI D3 steel
Disc hardness	58 ± 2 HRC
Pin materials	CBN, PCBN
Loads	10, 20, 30 N
Sliding speed	1.0 m/s
Sliding distance	1000 m
Test conditions	Dry, Eco-friendly lubricant
Temperature	Ambient

Fig. 8 shown about in the coefficient of friction increased with applied load under both dry and lubricated conditions. Under dry sliding, the friction coefficient was consistently higher because of direct asperity interaction between the pin and the D3 disc. In contrast, the eco-friendly lubricant significantly reduced friction at all loads by forming a protective boundary film at the contact interface. PCBN exhibited slightly lower friction than CBN under both environments, indicating better sliding stability and resistance to interfacial damage. At 30 N, the friction coefficient decreased from 0.71 to 0.48 for CBN and from 0.66 to 0.43 for PCBN when the eco-friendly lubricant was used. This corresponds to an approximate friction reduction of 32.4% for CBN and 34.8% for PCBN.

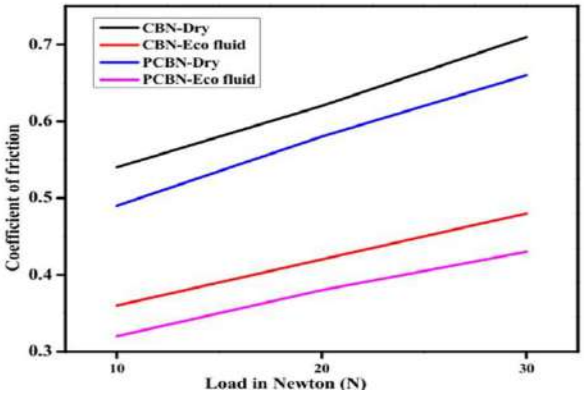

Figure 8: Coefficient of friction under dry and eco-friendly lubrication

3.2 Weight Loss of the pin

Weight loss increased with increasing normal load for both pin materials due to the higher real area of contact and greater severity of asperity deformation it has demonstrated in Fig. 9. The eco-friendly lubricant substantially reduced material loss by lowering frictional shear and suppressing adhesive interaction. PCBN again showed better wear resistance than CBN, which may be attributed to its improved toughness and resistance to edge micro-fracture.

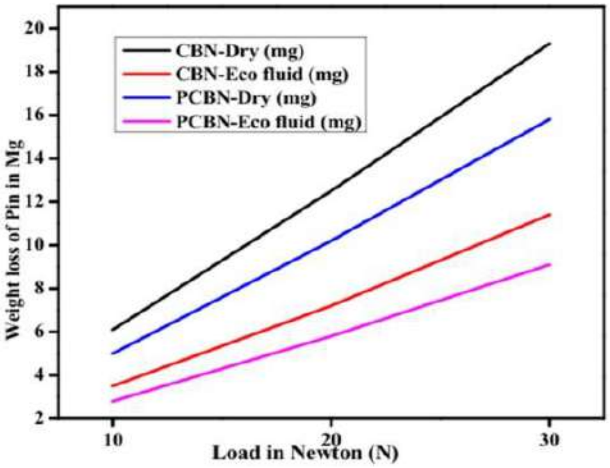

Figure 9: Weight Loss of the pin

3.3 Wear Volume

The curve of Wear volume shown in Fig. 10 was estimated from mass loss using:

$$V = \frac{\Delta W}{\rho} \tag{13}$$

where V is the wear volume, ΔW is the weight loss, and ρ is the density of the pin material. For comparative calculation, the density of CBN/PCBN was taken as 3.48 g/cm³, equivalent to 0.00348 g/mm

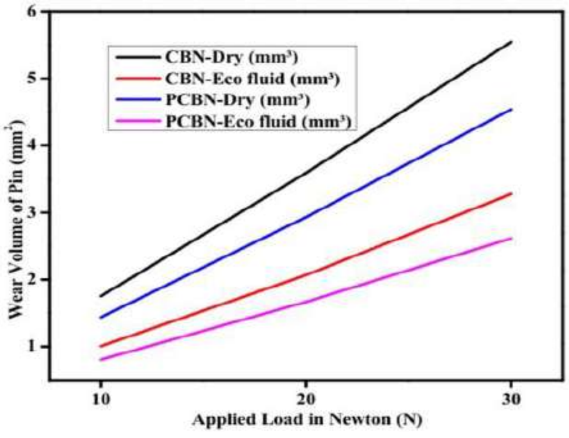

Figure 10: Wear volume of pins

The specific wear rate (K) was determined using the following equation:

$$K = \frac{V}{N \cdot L} \tag{14}$$

where: K = specific wear rate (mm³/N·m), N = applied load (N), L = sliding distance (m)

The Fig. 11 shows the specific wear rate increased slightly with load, indicating that wear severity intensified as the normal force increased. However, under eco-friendly lubrication, the specific wear rate remained significantly lower than under dry conditions. This confirms that the lubricant formed a stable tribofilm and reduced direct contact between the pin and D3 disc surface. At 20 N, the specific wear rate decreased from 1.796×10^{-4} to 1.035×10^{-4} mm³/N·m for CBN and from 1.466×10^{-4} to 0.834×10^{-4} mm³/N·m for PCBN. Overall, the wear rate reduction was about 39–42% with eco-friendly lubrication.

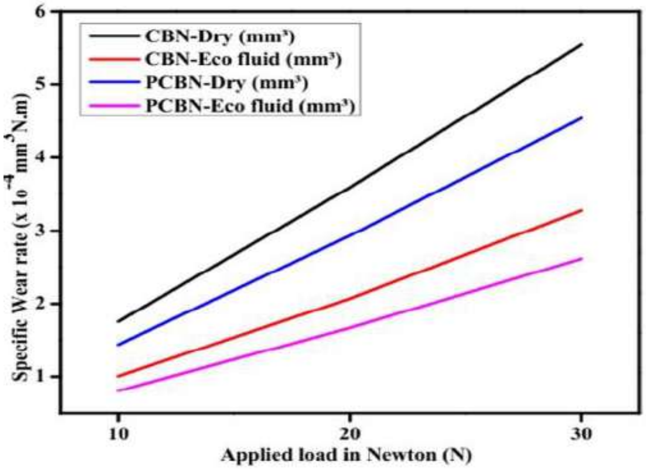

Figure 11: Specific Wear Rate

3.4 Comparative Performance of CBN and PCBN

PCBN performed better than CBN at all loads and in both lubrication environments. The improved performance of PCBN can be associated with its higher fracture toughness and better resistance to localized wear damage. Under dry conditions, both CBN and PCBN experienced severe adhesive and abrasive interaction with the D3 disc. Under eco-friendly lubrication, the lubricant reduced frictional heating and prevented direct metal-to-metal contact, producing smoother sliding behaviour and lower wear. The summary of tribological performance in shown in Table 9.

Table 9: Summary of tribological performance

Parameter	Best performer
Lowest friction	PCBN with eco-friendly lubricant
Lowest weight loss	PCBN with eco-friendly lubricant
Lowest wear volume	PCBN with eco-friendly lubricant
Lowest specific wear rate	PCBN with eco-friendly lubricant

3.5 Wear Mechanism Interpretation

Under dry sliding, the dominant wear mechanisms were: Adhesive wear, abrasive grooving, localized oxidation, and surface damage due to frictional heating. The higher loads intensified surface ploughing and material transfer, resulting in higher friction and material loss. With eco-friendly lubrication, the dominant mechanisms shifted toward: Boundary film lubrication, mild abrasive wear, reduced adhesive interaction, and improved thermal control. The polar constituents of the eco-friendly lubricant likely adsorbed on the contact surfaces and formed a lubricating film, reducing shear stress and wear severity. Friction coefficient increased with load for both pin materials under both environments. Eco-friendly lubrication reduced friction by about 30–35% compared with dry sliding. Weight loss and wear volume increased with load, but were substantially lower under lubrication. Specific wear rate was lower for PCBN than CBN at all loads.

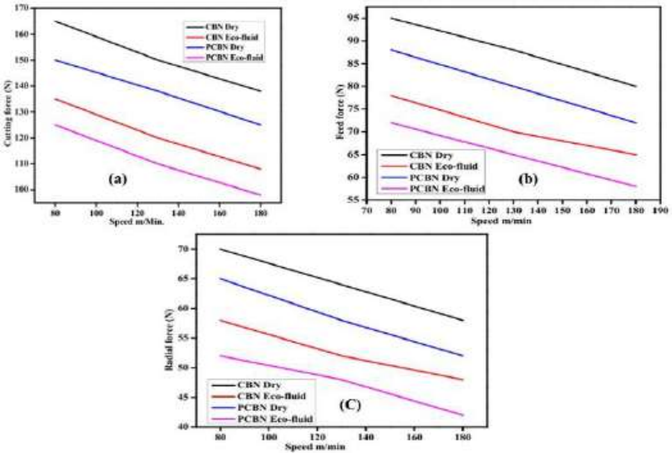

Figure 12: (a) Cutting force (b) Feed Force and (c) Radial force

3.6 Cutting Force Analysis in CNC Turning

Cutting force is a critical parameter in hard turning as it directly influences tool wear, surface finish, energy consumption, and machining stability. Table 10 presents the experimental conditions employed during the hard turning of AISI D3 steel. The workpiece material selected for the study was AISI D3 steel with a hardness of 58 ± 2 HRC, representing a highly hardened material commonly used in wear-resistant applications. Machining was performed using CBN/PCBN cutting tools, which are well suited for hard turning operations due to their excellent hardness, thermal stability, and wear resistance. The experiments were conducted at three different cutting speeds of 80, 130, and 180 m/min to investigate the influence of cutting velocity on machining performance. To isolate the effect of cutting speed, the feed rate (0.10 mm/rev) and depth of cut (0.75 mm) were maintained constant throughout all trials. Furthermore, machining was carried out under both dry and eco-friendly fluid-assisted lubrication conditions, enabling a comparative assessment of sustainable cooling and lubrication strategies. These controlled experimental parameters provide a reliable basis for evaluating tool performance, surface quality, cutting forces, and other machining responses under varying cutting environments.

The Fig. 13 shows in Cutting Forces which are the cutting force feed force and radial forces. The effect of Cutting Speed, cutting force (Fc) decreases with increasing cutting speed. This is due to thermal softening of the workpiece at higher speeds, which reduces shear strength. This evaluation shows CBN dry → 165 N → 138 N (↓16%) PCBN eco → 125 N → 98 N (↓21%)

Table 10: Experimental Conditions

Parameter	Value
Workpiece material	AISI D3 steel
Hardness	58 ± 2 HRC
Tool material	CBN / PCBN
Cutting speeds	80, 130, 180 m/min
Feed rate	0.10 mm/rev
Depth of cut	0.75 mm
Lubrication	Dry, Eco-friendly fluid

The effect of Lubrication in Eco-friendly cutting fluid reduces cutting forces significantly due to: Reduced friction at tool–chip interface, Formation of lubricating film, and Improved chip flow The Force reduction was CBN → ~18–22%, PCBN → ~20–25%. The Effect of Tool Material (CBN vs PCBN) PCBN shows lower cutting forces than CBN under all conditions due to better fracture toughness, improved edge stability, and a lower friction coefficient. In this studies it has finding are that cutting force decreases with increasing cutting speed, and Eco-friendly lubrication reduces forces by ~20%. PCBN performs better than CBN in all cases, Feed and radial forces follow similar trends.

3.7 Surface Roughness Analysis

Surface roughness is a key indicator of machining quality and is strongly influenced by cutting speed, tool material, and lubrication conditions. In this study, surface roughness (Ra) was measured using a contact profilometer (ISO 4287) after CNC turning of AISI D3 steel using CBN and PCBN tooling in this regard, the experimental condition given in Table 10.

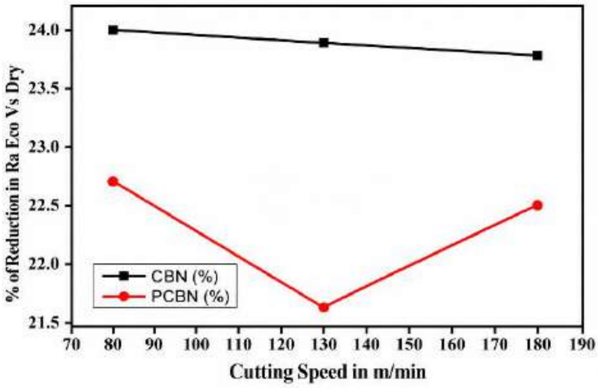

Figure 13: Cutting force (b) Feed Force and (c) Radial force

The results of Surface Roughness are shown in fig. 14. It has been shown the Effect of Cutting Speed Surface roughness decreases with increasing cutting speed. This is due to: Reduced built-up edge formation, Improved chip flow, Thermal softening of material. The CBN Dry → 1.25 → 0.92 µm (↓26%) PCBN Eco → 0.85 → 0.62 µm (↓27%). The Effect of Lubrication with the Eco-friendly lubricant significantly improves surface finish. Improvement mechanism: Like Reduces friction at tool–work interface Minimizes tool vibration Prevents adhesion and material tearing. The improvement shows CBN → ~20–25% reduction, PCBN → ~22–28% reduction. Also, the effect of Tool Material (CBN vs PCBN) is PCBN provides better surface finish than CBN due to the higher edge stability, Lower wear rate, reduced micro-chipping.

Mechanism Explanation in Dry Turning High friction → surface tearing, Built-up edge formation, Irregular feed marks. Eco-Friendly Lubrication: Formation of lubricating film Smooth chip flow, Reduced tool wear, Improved surface integrity, The main finding are (i) Surface roughness decreases with cutting speed (ii) Eco-fluid improves Ra by 20–25%.(iii) PCBN produces better surface finish than CBN.(iv) Best condition: PCBN + Eco-fluid + 180 m/min.

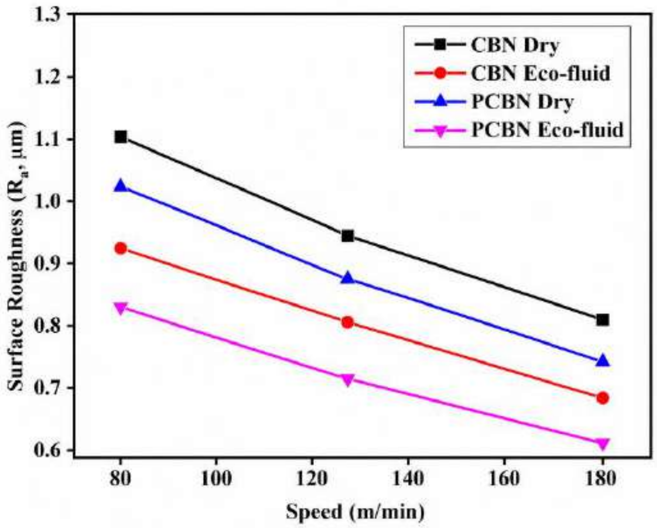

Figure 14: Surface Roughness (Ra, µm)

Tool wear is a critical indicator of machinability in hard turning operations as it directly influences dimensional accuracy, surface integrity, cutting forces, and tool life. In the present investigation, flank wear (VB) was evaluated during CNC turning of hardened AISI D3 steel (58 ± 2 HRC) using CBN and PCBN cutting inserts under dry and eco-friendly lubrication conditions. The experiments were conducted at cutting speeds of 80, 130, and 180 m/min, while maintaining a feed rate of 0.1 mm/rev and a depth of cut of 0.5 mm. Flank wear measurements were performed in accordance with ISO 3685 using a toolmaker's microscope with a resolution of 1 µm. The results revealed that flank wear increased progressively with increasing cutting speed for both tool materials under all machining environments. This behavior is attributed to the elevated temperature generated at the tool–workpiece interface at higher cutting speeds, which intensifies wear mechanisms such as abrasion, adhesion, and diffusion. A comparative analysis of the wear behavior demonstrated that the highest flank wear was recorded for the CBN tool under dry machining at 180 m/min, reaching approximately 0.29 mm, which is close to the commonly accepted tool failure criterion of 0.30 mm. Conversely, the PCBN tool operating under eco-friendly lubrication exhibited the lowest wear at the same cutting speed, with a flank wear of only 0.16 mm. The application of eco-friendly lubrication significantly reduced tool wear across all cutting speeds by lowering friction and cutting temperature, thereby enhancing tool life and machining performance. Furthermore, PCBN tools consistently exhibited superior wear resistance compared to CBN tools, confirming their suitability for high-speed hard turning applications.

The flank wear increased with increasing cutting speed for both CBN and PCBN tools under dry as well as lubricated conditions. This is mainly because higher cutting speed increases the temperature at the tool–workpiece interface, which accelerates wear processes such as abrasion, adhesion, and diffusion. The fig. 15 (a) to (d) shows comparative analysis under dry turning, the highest flank wear was observed for the CBN tool at 180 m/min, where the wear reached 0.29 mm, approaching the commonly accepted tool rejection criterion of 0.30 mm. In contrast, under the same cutting condition, the PCBN tool under eco-friendly lubrication showed the lowest wear among the high-speed cases, with a flank wear of 0.16 mm. The eco-friendly cutting fluid significantly reduced flank wear at all speeds.

At 80 m/min, flank wear for CBN decreased from 0.16 mm to 0.11 mm, representing a reduction of about 31.3%. At 130 m/min, flank wear for PCBN decreased from 0.18 mm to 0.12 mm, representing a reduction of 33.3%. At 180 m/min, flank wear for CBN decreased from 0.29 mm to 0.20 mm, corresponding to a reduction of about 31.0%.

The tool wear results demonstrate that flank wear increases with cutting speed for both CBN and PCBN tools during hard turning of AISI D3 steel. Eco-friendly lubrication significantly reduces tool wear by decreasing friction and cutting temperature at the contact interfaces. PCBN tools showed better wear resistance than CBN tools under all machining conditions. The combination of PCBN tool and eco-friendly cutting fluid provided the best wear performance, indicating strong potential for sustainable and efficient hard turning operations. PCBN tools under eco-friendly lubrication exhibited the lowest wear rate, enhancing tool life by up to 30% compared to dry machining. Tool wear strongly depends on cutting speed, confirming the thermo-mechanical dominance in hard turning of AISI D3 steel. Sustainable lubrication strategies can effectively replace conventional cooling methods without compromising machining performance.

Tool Life Criterion (ISO Standard) According to the ISO 3685 tool life criterion, a flank wear of 0.30 mm is often taken as the end of useful tool life for single-point turning tools. Fig. 16 shows that, based on the present data: (i) CBN under dry condition at 180 m/min nearly reached tool failure limit. (ii) PCBN under eco-friendly lubrication remained well below the failure threshold even at high speed. This indicates that eco-friendly lubrication can significantly extend useful tool life, particularly when used with PCBN tools in hard turning applications.

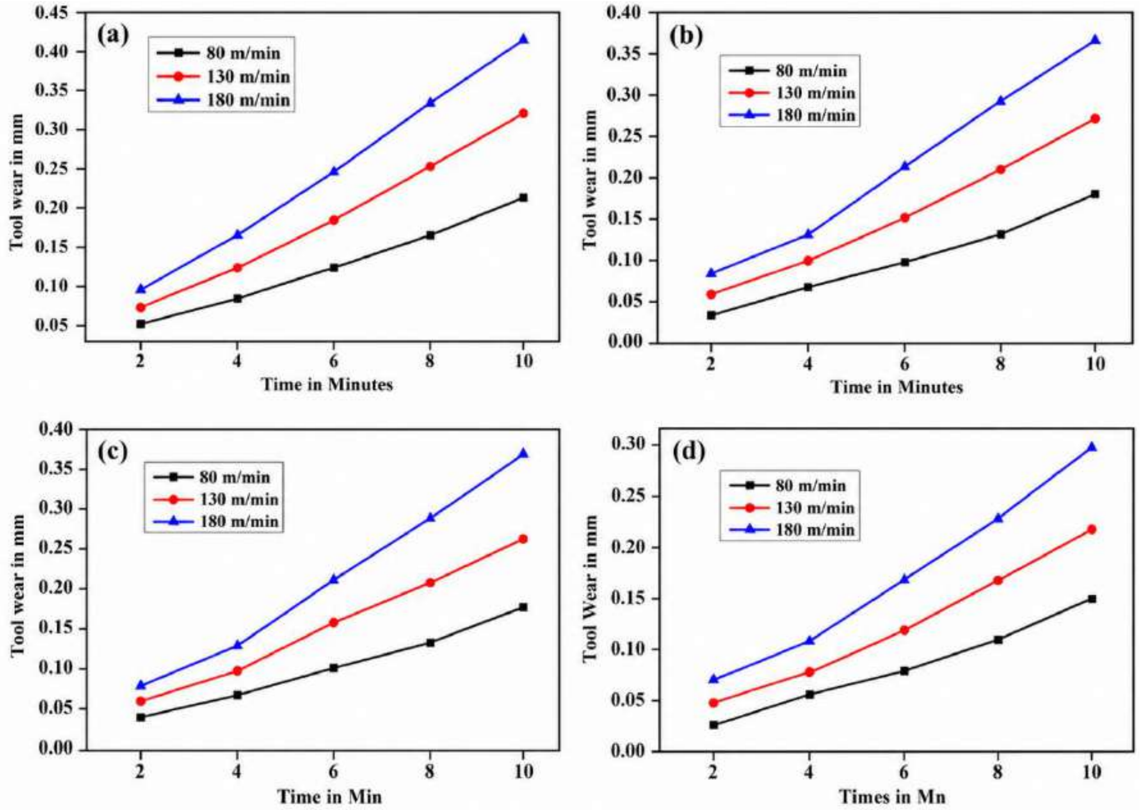

Figure 15: (a) CBN Tool – Dry Condition (b) CBN Tool – Eco-Friendly Lubrication. (c) PCBN Tool – Dry Condition. (d) PCBN Tool – Eco-Friendly Lubrication

The rheological behaviour of mineral-based (MB) and eco-friendly bio-based (BB) cutting fluids was investigated over a shear rate range of 10–1000 s^{-1} using a rotational rheometer equipped with a cone-plate geometry. The study was conducted within a temperature range of 30°C to 70°C to evaluate the flow characteristics of both fluids under conditions relevant to machining operations. The MB fluid consisted of a 2% oil-in-water emulsion, whereas the BB fluid was formulated as a 2% palm/vegetable oil-based emulsion. The relationship between shear stress and shear rate revealed distinct flow behaviours for the two cutting fluids. As shown in Fig. 17, the MB fluid exhibited an approximately linear increase in shear stress with increasing shear rate, indicating a nearly Newtonian flow behaviour. This suggests that the viscosity of the mineral-based emulsion remained relatively constant throughout the investigated shear rate range. In contrast, the BB fluid demonstrated a nonlinear shear stress–shear rate relationship, confirming its non-Newtonian characteristics. The deviation from linearity indicates that the viscosity of the bio-based fluid changes with applied shear, which is commonly associated with shear-thinning behaviour. Such rheological characteristics can be advantageous in machining applications, as the fluid maintains sufficient viscosity at low shear rates for effective lubrication while exhibiting reduced resistance to flow at high shear rates encountered in the cutting zone. Furthermore, the presence of natural fatty acid molecules in the bio-based emulsion contributes to enhanced lubricity and film-forming capability. Overall, the results indicate that the eco-friendly bio-based cutting fluid possesses superior adaptive flow characteristics compared with the conventional mineral-based fluid, making it a promising sustainable alternative for advanced machining processes.

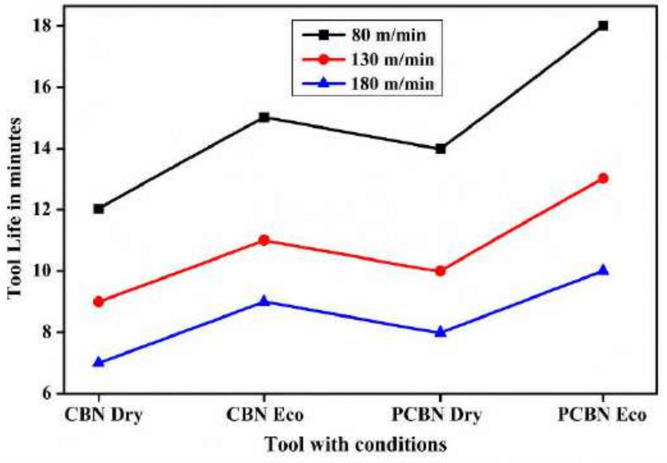

Figure 16: Estimated Tool Life (minutes

The rheological characteristics of mineral-based (MB) and eco-friendly bio-based (BB) cutting fluids were investigated over a shear rate range of 10–1000 s^{-1} using a rotational rheometer with cone-plate geometry. The study was conducted within a temperature range of 30–70°C to simulate practical machining conditions. The MB fluid consisted of a 2% oil-in-water emulsion, whereas the BB fluid was formulated using a palm/vegetable oil-based emulsion. Fig. 17 illustrates the relationship between shear stress and shear rate for both fluids. The MB fluid exhibited an approximately linear relationship, indicating near-Newtonian flow behavior, while the BB fluid displayed a nonlinear response, confirming its non-Newtonian nature.

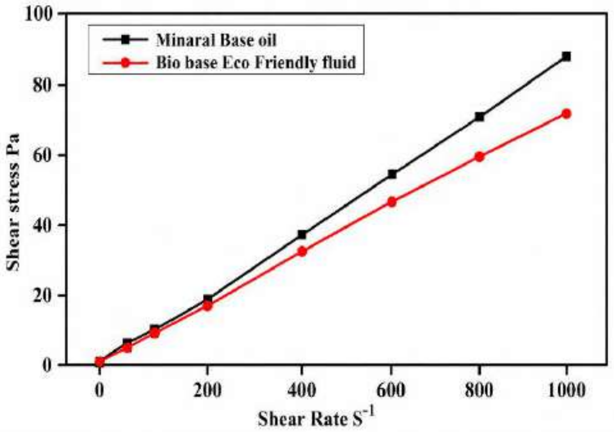

Figure 17: Shear Stress v/s Shear Rate (a) Mineral-Based Fluid

Analysis using the Power Law model ($\tau = K\gamma^n$) revealed that the MB fluid possessed a flow behavior index of approximately 0.98, signifying nearly Newtonian characteristics. In contrast, the BB fluid exhibited a lower flow behavior index of approximately 0.90, indicating pronounced shear-thinning or pseudo-plastic behavior. The calculated consistency indices were 0.88 Pa·s^n and 1.15 Pa·s^n for the MB and BB fluids, respectively. The observed non-Newtonian behavior of the bio-based fluid can be attributed to the presence of long-chain fatty acids and intermolecular interactions within the emulsion structure. The viscosity profiles further highlighted the differences between the two fluids. The MB fluid maintained an almost constant viscosity throughout the investigated shear rate range, whereas the BB fluid exhibited a gradual reduction in viscosity with increasing shear rate. At a low shear rate of 10 s^{-1}, the BB fluid showed a higher viscosity (0.120 Pa·s) than the MB fluid (0.095 Pa·s), indicating superior load-carrying capacity and enhanced lubricating film formation. However, as the shear rate increased to 1000 s^{-1}, the viscosity of the BB fluid decreased significantly to approximately 0.072 Pa·s, approaching that of the mineral-based fluid shown in Fig. 18. This adaptive rheological behavior is particularly advantageous for machining applications, as it provides strong boundary lubrication under low-shear conditions while reducing viscous resistance and energy consumption at high shear rates. Consequently, the bio-based cutting fluid demonstrates excellent potential for sustainable machining and minimum quantity lubrication (MQL) applications by combining effective lubrication, improved fluid mobility, and environmentally friendly characteristics.

The effect of temperature on the viscosity of mineral-based (MB) and bio-based eco-friendly (BB) cutting fluids was investigated over a temperature range of 30°C to 70°C at a constant shear rate of 100 s^{-1}. As illustrated in Fig. 19, both fluids exhibited a gradual reduction in viscosity with increasing temperature, which is attributed to enhanced molecular mobility and the weakening of intermolecular forces at elevated temperatures. Despite this common trend, the bio-based fluid consistently maintained higher viscosity values than the mineral-based fluid throughout the entire temperature range. At 70°C, the viscosity of the BB fluid was approximately 0.072 Pa·s, compared with 0.060 Pa·s for the MB fluid, indicating superior viscosity retention and thermal stability of the eco-friendly formulation.

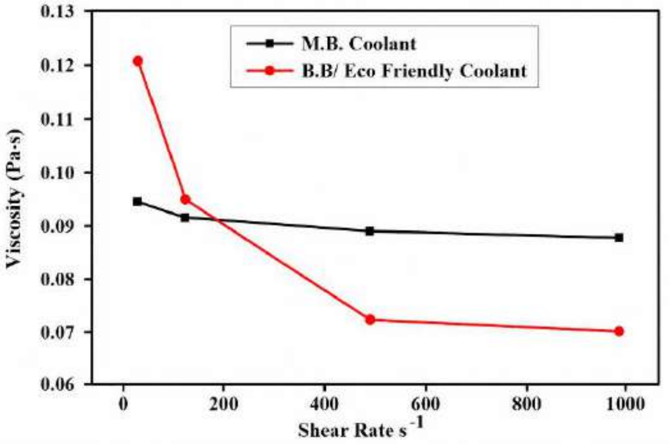

Figure 18: Viscosity V/S Shear rate

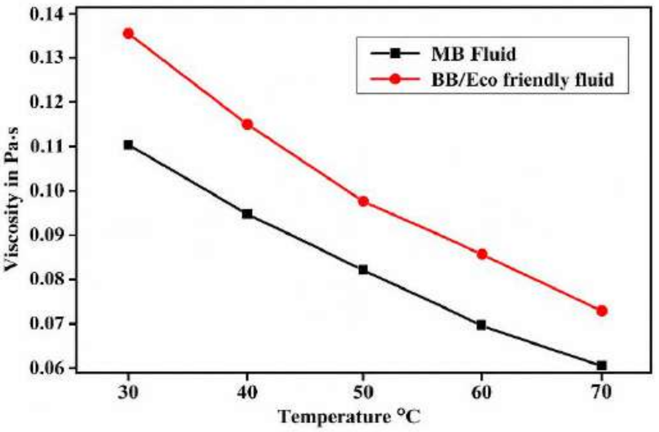

Figure 19: Shear Stress v/s Shear Rate (a) Mineral-Based Fluid

The enhanced thermal performance of the BB fluid can be attributed to the higher polarity and stronger intermolecular interactions of vegetable oil molecules, which provide greater resistance to thermal degradation than conventional mineral oils. This characteristic is particularly important in machining operations, where high temperatures generated at the tool–chip interface can accelerate lubricant breakdown and reduce lubrication effectiveness. The ability of the bio-based fluid to maintain a stable lubricating film under elevated temperatures contributes to improved cooling, reduced friction, and enhanced tool protection.

The present findings demonstrate the rheological advantages and practical suitability of eco-friendly cutting fluids for sustainable manufacturing applications. The superior viscosity retention, combined with previously observed shear-thinning behavior, highlights the capability of bio-based lubricants to adapt to varying machining conditions. These characteristics make eco-friendly cutting fluids highly attractive for advanced metal cutting operations, particularly in high-speed and minimum quantity lubrication (MQL) environments, where lubricant stability, efficient flow behavior, and environmental sustainability are essential requirements for achieving improved machining performance and reduced ecological impact.

4. Conclusions and Recommendations

The present study systematically evaluated the rheological behaviour of eco-friendly (bio-based) cutting fluids in comparison with conventional mineral-based emulsions, with particular emphasis on their suitability for sustainable machining applications.

The results clearly demonstrate that the eco-friendly cutting fluid exhibits non-Newtonian shear-thinning behaviour, characterized by a lower flow behaviour index (n<1n < 1n<1). This rheological response provides a distinct functional advantage: the fluid maintains higher viscosity at low shear rates, ensuring robust lubricating film formation and improved load-carrying capacity, while simultaneously exhibiting reduced viscosity at high shear rates, which facilitates smoother flow, enhanced penetration into the tool–chip interface, and lower energy dissipation during machining.

Furthermore, the eco-friendly fluid shows superior thermal stability, retaining higher viscosity across the investigated temperature range (30-70°C). This characteristic is critical under high-speed machining conditions, where elevated temperatures typically degrade lubricant performance. The enhanced thermal resistance is attributed to the intrinsic molecular structure and polarity of vegetable oil-based constituents, which promote stronger intermolecular interactions and stable film formation.

From a tribological standpoint, the adaptive viscosity behaviour of the bio-based fluid enables effective performance across multiple lubrication regimes, ranging from boundary to mixed and hydrodynamic conditions. The presence of polar functional groups further enhances surface adsorption, contributing to the formation of a protective tribo-film that minimizes friction and wear. Comparative analysis confirms that the eco-friendly cutting fluid outperforms the mineral-based counterpart in terms of lubrication efficiency, viscosity retention, and rheological adaptability, without compromising flow characteristics. These findings strongly support its applicability in advanced machining processes such as CNC turning, milling, and rolling.

In addition to technical performance, the eco-friendly fluid offers significant environmental benefits, including biodegradability, reduced toxicity, and compliance with green manufacturing standards.

In conclusion, the integration of eco-friendly cutting fluids in manufacturing systems not only enhances machining performance but also contributes to the broader objective of sustainable and environmentally responsible engineering practices, making it a promising direction for future industrial adoption and research.

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Cite this article as: H Ramamurthy Naik, Radhey Shyam Mishra, Ranganath M.S, Development and characterization of eco-friendly cutting fluid for CNC Turning of AISI D3 steel using CBN and PCBN tools, International Journal of Research in Engineering and Innovation, 10 (3), (2026), 115-129. *https://doi.org/10.36037/IJREI.2026.10305*