

PERFORMANCE ANALYSIS OF CASHEW NUT SHELL LIQUID-BASED HYBRID NANOFLUIDS FOR SUSTAINABLE MQL MACHINING OF EN-24 STEEL

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Sustainable machining demands metalworking fluids that minimize environmental hazards while maintaining surface integrity and tool life. In this study, a biodegradable hybrid nanofluid was developed using cashew nut shell liquid (CNSL) as the base oil blended with Al₂O₃, multi-walled carbon nanotubes (MWCNT), and graphene nanoplatelets (GnP) in a 70:20:10 ratio. The hybrid nanofluid was synthesized at three concentrations (0.5 wt %, 1 wt %, and 1.5 wt %) and applied in turning of EN-24 steel under minimum-quantity lubrication (MQL). Experimental trials were designed using the Taguchi L27 orthogonal array, and responses such as surface roughness, tool wear, and micro-hardness were analyzed through ANOVA and TOPSIS multi-criteria optimization. Results revealed that the 1.5 wt % hybrid nanofluid achieved the optimum performance by reducing surface roughness by ≈ 17 % and tool wear by ≈ 5 % relative to the lower concentrations while enhancing cooling and lubricating efficiency due to synergistic nanoparticle effects. The findings demonstrate that CNSL-based hybrid nanofluids are viable eco-friendly alternatives to mineral oils for precision turning applications.

Keywords: Sustainable machining; Hybrid nanofluid; Cashew nut shell liquid; EN-24 steel; Minimum-quantity lubrication; TOPSIS; Taguchi; ANOVA.

1. Introduction

Conventional machining operations generate substantial heat because of plastic deformation in the shear zone, friction at the tool–chip interface, and chip sliding along the rake face. Excessive temperature deteriorates surface finish, accelerates tool wear, and alters the metallurgical properties of the machined surface. Traditionally, metalworking fluids (MWFs) have been used to reduce

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friction, dissipate heat, and remove chips. However, mineral-oil-based fluids pose serious environmental and occupational-health risks, accounting for nearly 20 % of total production cost in typical metal-cutting operations [1]. The drive toward green manufacturing has therefore intensified research into bio-based lubricants and alternative cooling methods such as minimum-quantity lubrication (MQL).

The MQL technique delivers an atomized mist (typically 30–150 mL/h) of lubricant directly to the cutting zone, providing adequate cooling with minimal waste. Recent studies have shown that MQL using nanoparticle-enriched fluids can markedly improve heat dissipation and tribological behavior while reducing the carbon footprint [2,3]. Among emerging bio-lubricants, cashew nut shell liquid (CNSL) has attracted attention because it is a renewable by-product containing unsaturated phenolic compounds that exhibit strong film-forming and antioxidative properties [4].

While mono-nanofluids such as Al_2O_3 or CuO improve either thermal conductivity or lubricity, they often suffer from limited stability. Hybrid nanofluids, obtained by combining two or more nanoparticles in a base fluid, overcome this limitation through synergistic interactions that enhance both thermal and rheological characteristics [5]. For instance, Al_2O_3 provides high hardness and thermal conductivity, MWCNT offers excellent heat-transport channels, and GnP contributes superior tribological performance due to its layered structure [6].

Despite several investigations into nanofluid-assisted MQL machining, there remains limited information on the combined use of CNSL and multi-component nanoparticles in turning of hardened alloy steels such as EN-24. Previous works have primarily focused on vegetable oils like palm or soybean or on single nanoparticle systems. Vegetable-oil-based nanofluids have been reported to significantly improve heat transfer, lubrication, and tool life under MQL conditions, with hybrid nanofluids outperforming mono-nanoparticle systems due to synergistic effects [7]. The use of Al–SiC nanofluid-assisted MQL during turning of EN-24 steel resulted in reduced cutting temperature, tool wear, and surface roughness owing to enhanced cooling and lubrication at the tool–chip interface [8]. Hybrid nano-MQL strategies have been shown to substantially enhance the machinability of nickel-based superalloys by improving heat dissipation, stabilizing cutting forces, and minimizing tool wear [9]. Nanofluid-based MQL machining provides superior tribological behavior and thermal regulation compared to conventional lubrication methods, establishing it as an effective and sustainable cooling–lubrication technique [10]. Mono and hybrid nano-cutting fluids under MQL conditions have been demonstrated to reduce friction, adhesion, and thermal damage, thereby improving surface integrity and overall machining sustainability [11].

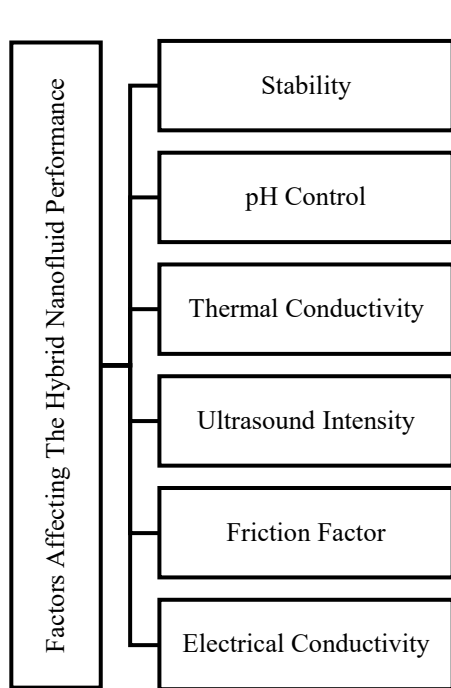


Fig. 1. Factors Affecting the Hybrid Nanofluid Performance [12,13,14]

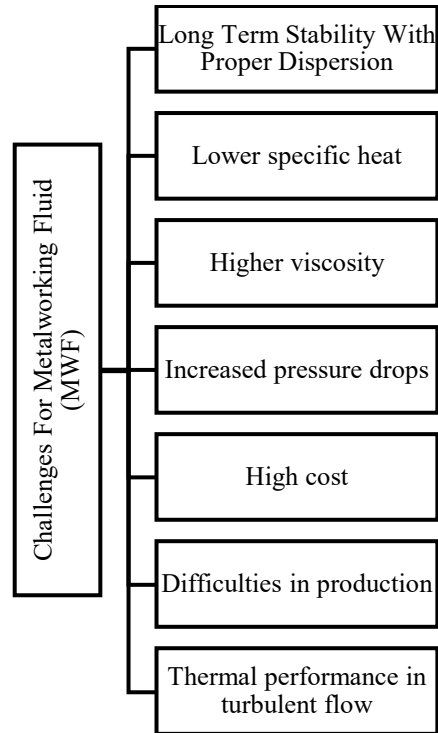


Fig. 2. Challenges for Metalworking Fluid (MWF) [12,13,14]

In this context, the present study provides a systematic evaluation of the machinability, surface integrity, and eco-performance of CNSL-based hybrid nanofluids, with the following objectives:

1. Synthesize and characterize CNSL-based hybrid nanofluids containing Al_2O_3 , MWCNT, and GnP nanoparticles at various concentrations.
2. Investigate their influence on surface roughness, tool wear, and micro-hardness during turning of EN-24 steel under MQL conditions.
3. Apply Taguchi design, ANOVA, and TOPSIS multi-criteria optimization to determine the most significant parameters and optimal machining configuration.

This work contributes to sustainable manufacturing by transforming a low-cost agro-waste product into an efficient, biodegradable metalworking fluid capable of enhancing machinability while mitigating environmental impact. Fig. 1 and Fig. 2 represents the factors affecting the hybrid nanofluid performance and challenges in metal working fluids respectively.

2. Materials and methods

2.1 Preparation of Hybrid Nanofluid

To prepare 0.5 %, 1 %, and 1.5 % concentrated hybrid nanofluid, commercially available nanoparticles of Al₂O₃, MWCNT, and GNP are added to CNSL in the proportions 70:20:10, respectively. Then nanofluid is kept under ultrasonic vibration continuously for 6 hours to get a uniform and stable suspension, an ultrasonic vibrator generating ultrasonic pulses of 400W at 33±3 kHz and to break down agglomeration of the nanoparticles the magnetic stirrer was used. The density, dynamic viscosity, and pH of the nanofluid are all measured once it is prepared and summarized in Table 1.

Figure 3 (a) column chart illustrates the values of density for each MWF viz; 0%, 0.5%, 1%, and 1.5% concentrated hybrid nanofluid. The density values in kg/m³ are 864.03, 879.94, 891.4 and 908. kg/m³ respectively. Figure 3 (b) column chart represents the values of dynamic viscosity for each MWF. Measurements of dynamic viscosity were conducted on Antom Par make digital viscometer with a computer-controlled temperature bath set at 40°C. Values in Pa.S are 0.05444, 0.07344, 0.08107 and 0.090495 respectively. The pH of CNSL is measured using the digital pH meter are 8.01, which indicates the CNSL is alkaline in nature. The pH of CNSL is similar to pH of sea water, egg and baking soda.

Table 1

Measurement of physical properties of prepared MWF					
Properties	Unit	0.00% Concentration	0.50% Concentration	1.00% Concentration	0.15% Concentration
Density	kg/m ³	864.03	879.945	891.4	908.775
Dynamic viscosity	Pa.S	0.05444	0.07344	0.08107	0.090495

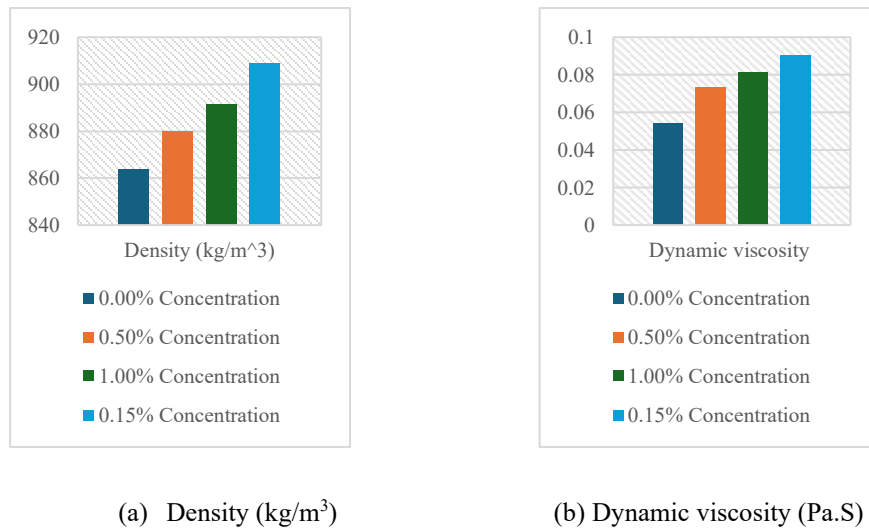


Fig. 3. The characterization of CNSL and hybrid nanofluid

2.2 Workpiece Materials

EN-24 Steel is a high-strength alloy steel with a high tensile strength, ductility, and wear resistance. The EN-24 steel material used to manufacture components such as gears, shafts, studs and bolts, etc. EN-24 steel's hardness is assessed using a micro-hardness tester, yielding a result of about 48-49 HRC. The composition of EN24 is shown in Table 2. Surface roughness of machined workpieces is assessed using a surface roughness tester/analyzer, tool wear is measured using tool makers microscope and micro hardness of machined workpiece is measured using Vickers micro hardness microscope, summarized in a Table-4.

Table 2

Chemical Composition of EN-24 Material

Element	Si	Cr	C	S	P	Mn	Mo	Ni
% Weight	0.35	1.40	0.44	0.04	0.035	0.70	0.35	1.70

2.3 Experimental Procedure

The MQL system is used to turn an EN-24 steel workpiece with a dimension of 40 mm x 50 mm on a lathe (Semi-automatic Retrofit machine) utilizing a CVD Coated Carbide insert as a tool under three different concentrations of hybrid nanofluid mist. Fig. 4 and 5 demonstrate the experimental arrangement for turning operations (MQL setup). The flow rate and pressure of the MQL system are set at 150 ml/hr and 4 bar, respectively. The nozzle (1mm) is positioned in the plane of the cutting tool at a 30° angle to the feed direction and 5 cm distant from the tool-workpiece contact, allowing the MWF to fall into the cutting zone. At various

lubrication environments, the turning is done according to the cutting conditions listed in Table 3. For the Design of Experiment, three machining parameters and their three levels are taken into account (DOE). All of the studies were carried out with a Taguchi L27 orthogonal array. Each experiment was carried out thrice and average value was considered.

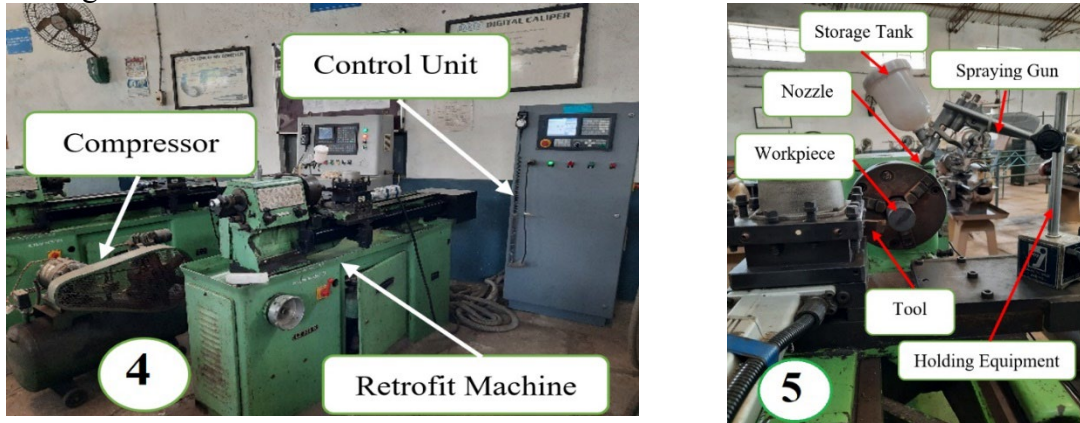


Fig. 4 & 5. Experimental setup with MQL

Table 3

Machining parameters and their levels

Control Parameters	Symbol	Unit	Level		
			I	II	III
Speed	V_c	m/min	40	70	100
Feed	f	mm/rev	0.1	0.15	0.2
Depth of cut (DOC)	a_p	mm	0.1	0.3	0.5

The machining parameters were selected at three levels (I, II, and III) to represent low, medium, and high operating conditions commonly encountered in turning of EN-24 steel. Level I corresponds to conservative cutting conditions to minimize tool wear and thermal effects, Level II represents moderate conditions typically used in industrial practice, and Level III denotes aggressive cutting conditions intended to evaluate the performance limits of the cutting fluid under higher mechanical and thermal loads. In addition The nanoparticle concentration was limited to 1.5 wt% based on practical and tribological considerations. At higher concentrations, nanofluids tend to exhibit increased viscosity and particle agglomeration, which can adversely affect spray stability in MQL systems and reduce lubrication effectiveness. Moreover, excessive solid loading may promote abrasive wear and nozzle clogging. Therefore, concentrations beyond 1.5 wt% were not considered in the present study.

2.4 Measurement of response parameters

2.4.1 Surface roughness measurement

The surface roughness (Ra) of the machined workpiece is a critical indicator of surface quality and functional performance. In the present study, surface roughness measurements were carried out using a Mitutoyo stylus-type surface roughness tester under three different concentrations of hybrid nanofluid-assisted MQL machining conditions. Surface roughness is influenced by machining parameters such as cutting speed, feed rate, and depth of cut, as well as by the cooling–lubrication environment and workpiece material properties. The measured Ra values for the three machining conditions are presented in Table 4. Figure 6 illustrates the steel specimen and the direction adopted for surface roughness measurement. Since the specimen diameter was significantly larger than the selected sampling length, the effect of surface curvature on the measurement was considered negligible. The measurements were performed along the axial direction (perpendicular to the circumferential feed marks generated during turning) to prevent the stylus from riding along the grooves and to obtain a representative and reliable Ra value.

2.4.2 Tool Wear measurement

Tool wear (TW) is the progressive breakdown of cutting tools as a result of prolonged usage. Increased cutting forces and temperatures, increased surface roughness, lower completed component precision, tool breakage, and a change in tool geometry can all lead to tool breakage. Under three different cooling settings, the tool wear of inserts is assessed using Mitutoyo's Toolmaker's microscope. The tool wear (measured in mm) for three different machining situations is shown in Figure 4. Tool wear was primarily characterized in terms of flank wear, which is the most commonly used indicator of tool degradation during turning operations. Flank wear occurs on the clearance face of the cutting insert due to continuous rubbing between the tool and the newly machined surface. The average flank wear width (VB) was measured along the tool–workpiece contact region as shown in Fig. 7.



Fig. 6 Specimen showing direction of surface roughness measurement

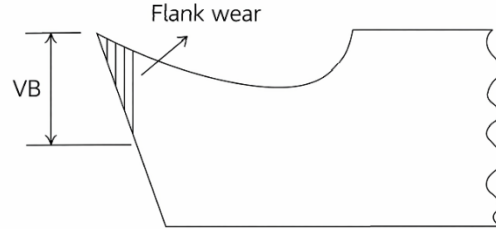


Fig. 7 Tool wear geometry

2.4.3. Micro-hardness

During the machining process, substantial amount of heat is generated around tool and workpiece thus hardness of workpiece is increases. The micro hardness of machine workpiece is measured using Vickers micro hardness tester. The micro hardness of workpiece under 1.5% concentrated hybrid nanofluid machining conditions are observed lower compared to the 0.5% and 1% concentrated hybrid nanofluid machining.

2.4.4. Chip Morphology

During the turning operation, chips of different colors and morphologies were observed under various machining environments. In dry machining, elevated temperatures in the shear and cutting zones resulted in the formation of blue-colored chips, indicating severe thermal loading. In contrast, silver-colored chips were produced under 0.5%, 1%, and 1.5% concentrated HNFML conditions, suggesting improved cooling and lubrication due to enhanced thermal conductivity of the hybrid nanofluid. Under all HNFML conditions, the chips exhibited a curled and segmented morphology, which is typically associated with stable cutting and reduced friction at the tool–chip interface. Similar observations have been reported in nanofluid-assisted MQL machining studies [15].

Table 4

Experimental Results

Run No.	DOE			0.5% Concentration			1 % Concentration			1.5 % Concentration		
	Speed	Feed	DOC	Ra	TW	MH	Ra	TW	MH	Ra	TW	MH
1	40	0.1	0.1	1.466	0.085	498.2	1.278	0.077	492.5	1.348	0.064	486.4
2	40	0.1	0.3	1.512	0.175	534.5	1.356	0.164	529.1	1.349	0.157	523
3	40	0.1	0.5	1.568	0.128	531.4	1.387	0.159	525.7	1.365	0.143	519.1
4	40	0.15	0.1	1.289	0.115	520.1	1.107	0.103	514.9	1.049	0.096	508.3
5	40	0.15	0.3	1.614	0.204	540.2	1.398	0.194	534.5	1.382	0.185	528.4
6	40	0.15	0.5	1.629	0.233	567.8	1.419	0.281	562.1	1.398	0.274	556
7	40	0.2	0.1	1.753	0.293	524.4	1.507	0.139	518.7	1.478	0.121	512.6

8	40	0.2	0.3	1.833	0.238	549.5	1.633	0.227	544.2	1.521	0.219	538.1
9	40	0.2	0.5	2.078	0.304	576.5	1.835	0.314	570.8	1.659	0.304	564.7
10	70	0.1	0.1	1.327	0.093	514.7	1.109	0.087	509	1.093	0.074	502.9
11	70	0.1	0.3	1.406	0.183	535.1	1.201	0.173	529.6	1.196	0.165	523.7
12	70	0.1	0.5	1.407	0.224	556.9	1.214	0.256	551.2	1.204	0.241	545.1
13	70	0.15	0.1	1.385	0.124	520.4	1.167	0.114	514.7	1.122	0.105	508.6
14	70	0.15	0.3	1.418	0.217	541.6	1.235	0.204	535.9	1.328	0.198	529.8
15	70	0.15	0.5	1.466	0.295	568.2	1.325	0.295	562.5	1.348	0.285	556.4
16	70	0.2	0.1	1.759	0.159	526.5	1.515	0.142	520.8	1.517	0.137	514.7
17	70	0.2	0.3	1.733	0.245	550.3	1.487	0.237	544.6	1.452	0.224	538.5
18	70	0.2	0.5	1.951	0.318	586.5	1.689	0.323	580.1	1.578	0.318	574.7
19	100	0.1	0.1	0.944	0.102	515.5	0.829	0.097	509.8	0.557	0.183	503.4
20	100	0.1	0.3	1.043	0.191	536.5	0.889	0.184	530.7	0.646	0.175	524.7
21	100	0.1	0.5	1.234	0.217	565.6	1.026	0.279	559.9	0.896	0.269	553.8
22	100	0.15	0.1	1.139	0.137	523.1	1.003	0.125	517.4	0.763	0.118	511.3
23	100	0.15	0.3	1.261	0.223	544.8	1.058	0.217	539.1	0.974	0.204	533
24	100	0.15	0.5	1.405	0.301	569.5	1.184	0.304	563.5	1.173	0.297	557.4
25	100	0.2	0.1	1.562	0.168	531.4	1.363	0.153	525.7	1.354	0.146	519.1
26	100	0.2	0.3	1.683	0.257	552.3	1.424	0.249	546.6	1.423	0.234	540.5
27	100	0.2	0.5	1.892	0.311	591.5	1.643	0.336	585.8	1.541	0.327	579.7

3. Results and Discussion

3.1 Comparative study

3.1.1 Surface roughness

Surface roughness (Ra) directly affects fatigue life, tribological performance and dimensional precision. The experimental data show a consistent trend: 1.5 wt% CNSL-based hybrid nanofluid under MQL yields the lowest Ra values across the Taguchi runs when compared to 0.5 wt% and 1.0 wt% concentrations. For example, the averaged Ra values across all experimental runs decrease by ~17.3% for 1.5 wt% compared to 0.5 wt%. These tabulated results and per-run Ra values are reproduced from the experimental dataset. This improvement is attributable to two synergistic mechanisms reported in recent hybrid-nanofluid studies: (i) improved boundary-film formation and sustained lubricity from the CNSL base (bio-ester/phenolic constituents) and (ii) enhanced thermal conductivity and mending/polishing action from the mixed nanoparticle population (Al_2O_3 + MWCNT + GnP) which reduces instantaneous tool–chip temperature and micro-adhesion. Recent reviews and experiments confirm such combined effects for hybrid MQL fluids and report analogous magnitudes of Ra reductions when hybrid

nanoparticles are used [16]. The combined action of Al_2O_3 , MWCNT, and GnP enhances thermal conductivity and reduces friction at the tool–chip interface.



Fig. 8. Graphical representation of comparative study of the surface roughness

Where feed dominates roughness (as shown in S/N plots), the hybrid nanofluid magnifies the benefit of low-feed/high-speed combinations by sustaining a thinner, stronger lubricant film—hence the best Ra appears at the lowest feed and highest speed combinations in our study. These process-mechanism interpretations align with observations in recent MQL optimization and hybrid-fluid literature. Table 4 summarizes the findings of a comparison of surface roughness values for three different concentrated hybrid nanofluids. The comparative study of surface roughness is depicted in Fig. 8.

3.1.2 Tool wear

Tool flank wear (V_b) trends from the experiments indicate reduced wear with increasing nanofluid concentration, with the 1.5 wt % hybrid nanofluid showing the lowest mean tool wear across matched cutting conditions (Table 4). Quantitatively, tool wear decreased by approximately 5 % and ~3.1 % with 1.5 wt % relative to 0.5 wt % and 1.0 wt %, respectively. Mechanistically, the presence of GnP and MWCNT provides nano-solid lubrication (shear-facilitating, layered sliding), while Al_2O_3 particles contribute to thermal conduction and surface repair (mending). The combined effect lowers adhesive

wear and reduces localized temperature spikes that accelerate crater formation [17,18,19]. Lowest absolute wear values were observed at the lowest combinations of cutting speed, feed and depth of cut; however, the relative improvement due to hybrid-MQL is more pronounced at higher speeds, where thermal softening would otherwise accelerate wear. This indicates that the hybrid nanofluid is particularly effective in mitigating thermally induced wear, a phenomenon [20,21]. Overall, the enhanced anti-wear behavior achieved in the present investigation corroborates recently reported tribological mechanisms combining improved heat transfer, nano-mending, and layered solid-lubrication actions [22,23]. The comparative study of tool wear is depicted in Fig. 9.

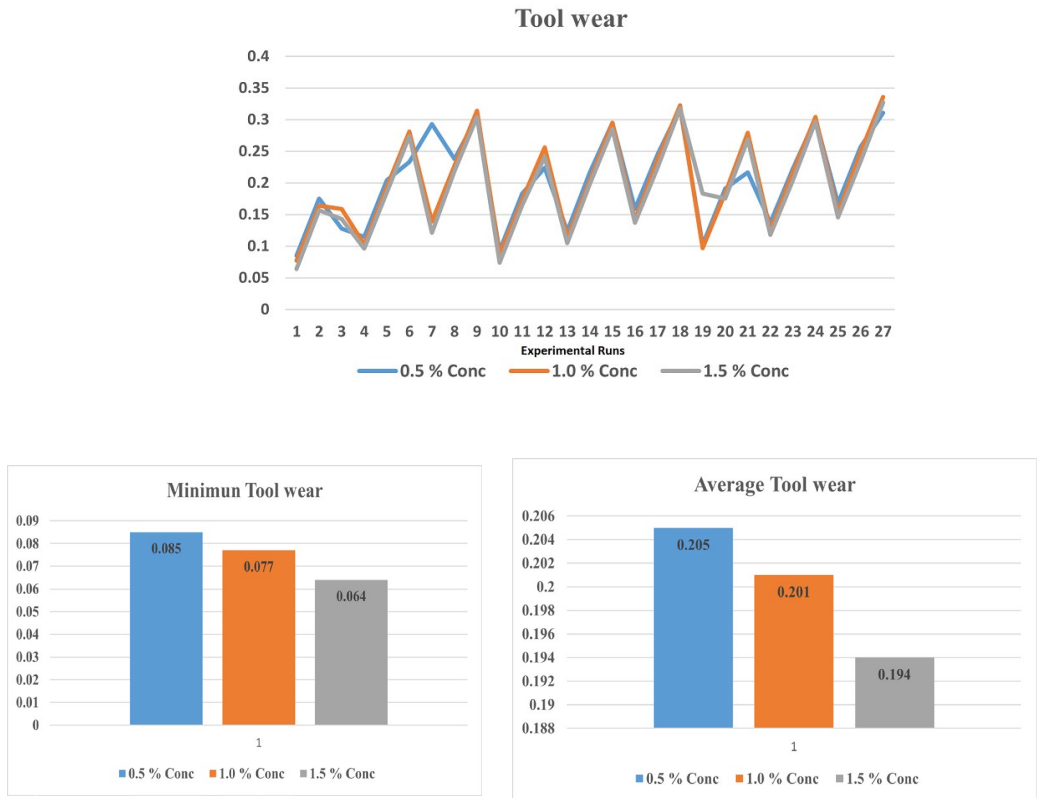


Fig. 9. Graphical representation of comparative study of the tool wear

3.1.3 Micro-hardness of machined workpiece

The high heat generated in the cutting zone results from a significant portion of the mechanical energy expended during chip removal operations being converted into thermal energy. This temperature rise at the tool–chip interface strongly influences machinability, affecting surface integrity, dimensional accuracy, and tool life [17]. Elevated temperatures accelerate diffusion and adhesion wear,

degrade the cutting-edge, and alter the microstructure of the machined surface [24]. Dry cutting produced the highest cutting-zone temperatures, consistent with earlier reports that absence of lubrication leads to excessive friction and localized thermal softening. In contrast, machining under hybrid nanofluid MQL (HNFML) conditions significantly reduced interface temperature owing to enhanced convective heat transfer and nano-film formation [18]. When comparing different concentrations, both minimum and average micro-hardness of the machined surface under 1.5 wt % HNFML conditions were found to be lower than those for 0.5 % and 1 % concentrations. This reduction in hardness reflects improved heat dissipation and reduced strain-hardening due to effective lubrication and cooling by the hybrid nanofluid [24]. The comparative analysis of *surface roughness*, *tool wear*, and *micro-hardness* across 0.5 %, 1 %, and 1.5 % concentrations (Sections 3.1.1–3.1.3) clearly indicates that 1.5 wt % HNFML improves the surface finish while simultaneously reducing tool wear and surface hardening, leading to superior chip formation and thermal balance [25,26]. Accordingly, the present study focuses subsequent investigation on the optimal 1.5 wt % hybrid nanofluid concentration. The comparative study of micro hardness is depicted in Fig. 10.

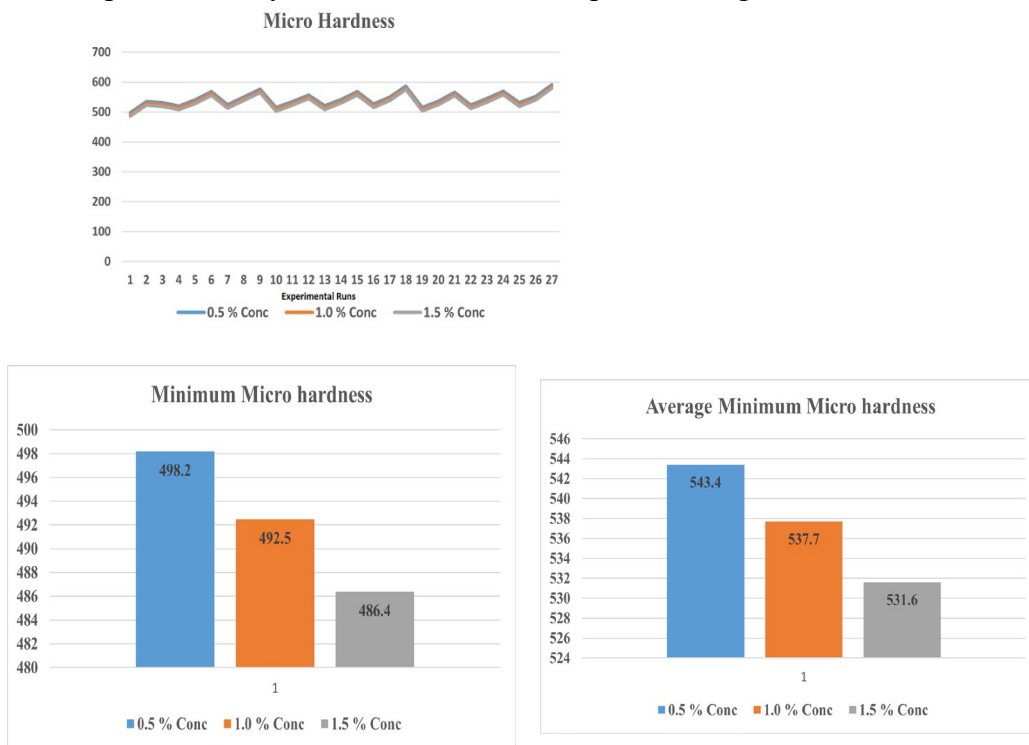


Fig. 10. Graphical representation of Comparative study of micro-hardness of machined workpiece

3.2 Response analysis

Preliminary experimental results indicated that the 1.5 wt% hybrid nanofluid consistently outperformed the lower concentrations in terms of surface roughness, tool wear, and micro-hardness. Therefore, for detailed parametric analysis and statistical evaluation, Taguchi design and ANOVA were performed by fixing the nanofluid concentration at 1.5 wt%, while varying the machining parameters. This approach allowed the influence of cutting parameters to be analyzed under the optimum lubrication condition.

The Taguchi technique is a method for minimizing variations in design parameters before optimizing the design to achieve mean target values for output parameters [27,28]. It employs customized orthogonal arrays for various variable parameters at various levels in order to investigate all design factors with the fewest possible experiments. The S/N ratio main effects plot depicts how each component influences the response characteristics. Figs. 11, 12, and 13 demonstrate how control factors like as speed, feed, and depth of cut effect surface roughness, tool wear, and microhardness. Tables 5, 6, and 7 exhibit the signal to noise ratio response tables for surface roughness, tool wear, and microhardness, respectively [29].

The impacts of input parameters (cutting speed, cutting feed, and cut depth) on the output parameter are depicted in Fig. 11. (Surface roughness). It can be seen from the graph that as the cutting speed increases, the surface roughness of the workpiece reduces. Cutting temperature rises as cutting speed increases. Thermal softening of the workpiece material happens as a result, resulting in material removal that is excessive, resulting in an increase in surface roughness. With the highest speed and lowest feed, the best surface roughness is achieved. Because shear angle increases with depth of cut, rubbing action and temperature increase, a greater depth of cut results in increased surface roughness [30].

At varying cutting speeds of 40, 70, 100 m/min, depth of cut 0.1, 0.3, 0.5 mm, and feed rate of 0.1, 0.15, 0.12 mm/rev, respectively, the impacts of input parameters (cutting speed, cutting feed, and depth of cut) on output parameter (tool wear) are shown in Figure 11. The tool wear rises as the speed, feed, and depth of cut increase, as seen in the graph. When compared to a high speed of 100 m/min, tool wear is reduced by around 20% at a spindle speed of 40 m/min. Similarly, increasing the cutting feed causes higher tool wear due to increased tool and workpiece contact time. Because load is imparted to the tool, the depth of cut rises as tool wear increases.

The high heat in the cutting zone is caused by a significant amount of the mechanical energy expended during chip removal operations. One of the most essential aspects in machinability is the temperature induced by heat. Because high temperatures have an impact on surface integrity, dimensional accuracy, tool life and wear, and other factors. The microhardness of machined workpiece increases with increase in speed feed and depth of cut which is shown in Fig. 13.

Taguchi Analysis for surface roughness: 1.5 % concentrated HNMQL versus Speed (RPM), Feed (mm/rev), Depth of cut (mm)

Table 5

Response table for means (smaller-is-better) for surface roughness

Level	Speed m/min	Feed mm/rev	Depth of cut (mm)
1	1.394	1.073	1.142
2	1.315	1.171	1.252
3	1.036	1.503	1.351
Delta	0.358	0.43	0.209
Rank	2	1	3

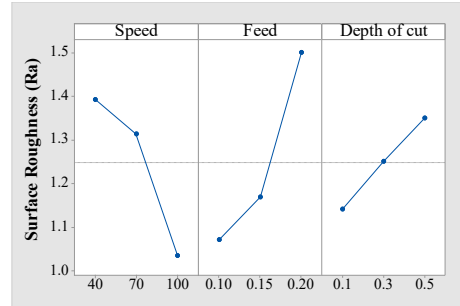


Fig. 11. Effects of input parameters on Surface roughness

Table 5 indicates the most significant parameters for surface roughness. For the surface roughness the cutting feed (mm/rev) is the most significant parameter and then speed (m/min). Similarly, Table 6 and 7 indicates the most significant parameters for tool wear and micro hardness of machined workpiece. For the tool wear and micro hardness of machined workpiece, depth of cut (mm) is the most significant parameter and then feed rate (mm/rev).

Taguchi Analysis for tool wear: 1.5% concentrated HNMQL versus Speed (RPM), Feed (mm/rev), Depth of cut (mm)

Table 6

Response table for means (smaller-is-better) for tool wear

Level	Speed	Feed	Depth of cut (mm)
	m/min	mm/rev	
1	0.1737	0.1634	0.116
2	0.1941	0.1958	0.1957
3	0.217	0.2256	0.2731
Delta	0.0433	0.0621	0.1571
Rank	3	2	1

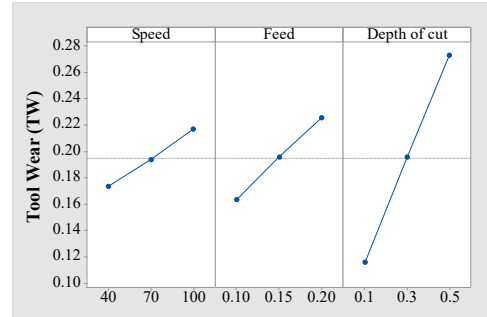


Fig. 12. Effects of input parameters on tool wear

Taguchi Analysis for micro hardness: 1.5 % concentrated HNMQL versus Speed (RPM), Feed (mm/rev), Depth of cut (mm)

Table 7

Response table for means (smaller-is-better) for micro-hardness

Level	Speed	Feed	Depth of cut (mm)
	m/min	mm/rev	
1	526.3	520.2	507.5
2	532.7	532.1	531.1
3	535.9	542.5	556.3
Delta	9.6	22.3	48.8
Rank	3	2	1

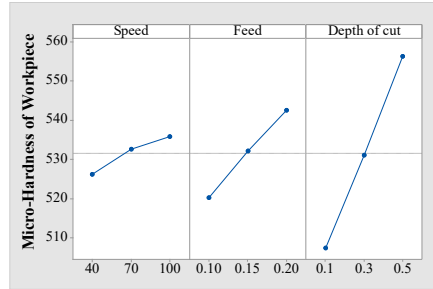


Fig. 13. Effects of input parameters on micro hardness

3.3 Analysis of variance (ANOVA)

Since the nanofluid concentration was fixed at its optimal level (1.5 wt%), it was not included as a control factor in the ANOVA, and the analysis focused on the relative significance of machining parameters.

The conclusion is drawn based on the results of the ANOVA analysis. According to Table 8 and the P value, the cutting feed (mm/rev) is the most significant parameter that contributes to surface roughness, accounting for about 43.46 % of the total. The second parameter that contributes to surface roughness is the cutting speed (m/min), which accounts for approximately 30.29 % of the total. The depth of cut (mm), which contributes around 09.35% to surface roughness, is the third parameter. The relevant parameter and percentage contribution are shown in Table 8.

Table 8

General Linear Model for surface roughness: HNFML versus Speed (RPM), Feed (mm/rev), Depth of cut (mm)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Cont.	Significance
(v)	2	0.6367	0.31837	17.96	0	30.29741	Significant
(f)	2	0.9135	0.45676	25.77	0	43.46895	Significant
(ap)	2	0.1967	0.09837	5.55	0.012	9.359981	Significant
Error	20	0.3545	0.01773			16.8689	
Total	26	2.1015					

Model Summary	
S	0.1334
R-sq	83.13%
R-sq(adj)	78.07%
R-sq(pred)	69.25%

The depth of cut (mm) is the sole important element that affects tool wear, with the cutting speed accounting for around 72.90 % of the total. The second component that contributes to tool wear is the cutting feed (mm/rev), which accounts for approximately 11.40% of the total. The cutting speed (m/min), which adds around 5.55% to tool wear, is the third component. The relevant parameter and percentage contribution are shown in Table 9.

Table 9

General Linear Model for tool wear: HNFML versus Speed (RPM), Feed (mm/rev), Depth of cut (mm)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Cont	Significance
(v)	2	0.008459	0.00423	5.48	0.013	5.551836	Significant
(f)	2	0.01737	0.00869	11.24	0.001	11.40033	Significant
(ap)	2	0.111085	0.05554	71.9	0	72.90764	Significant
Error	20	0.01545	0.00077			10.14019	
Total	26	0.152364					

Model Summary	
S	0.0279
R-sq	89.8 %
R-sq(adj)	86.8 %
R-sq(pred)	81.5 %

3.4 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method

TOPSIS (Technique for order preference by similarity to ideal solution) is a simple and effective Multi-Criteria Decision Making (MCDM) tool that may be utilized in a variety of applications, such as process parameter selection in manufacturing. TOPSIS is one of the multi-criteria decision-making approaches (MCDM) that is used to address multi-objective issues [31]. In this method, the steps listed below were used.

i. Matrix preparation

In this experimental work, there are 3 response variable and 9 ways to conduct experiment. Hence, the matrix is [27,3].

ii. Calculation of normalized matrix

$$\bar{X}_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^m X_{ij}^2}}$$

iii. Calculation of weighted normalized matrix (V_{ij})

In this work, equal weightage was given to surface roughness and tool wear.

$$V_{ij} = \bar{X}_{ij} \times W_j$$

iv. Calculation of ideal positive (S_i⁺) and ideal negative (S_i⁻) solution
Ideal positive (S_i⁺) and Ideal negative (S_i⁻) solutions are calculated from equations below.

$$S_i^+ = \left[\sum_{j=1}^m (V_{ij} - V_j^+)^2 \right]^{0.5}$$

$$S_i^- = \left[\sum_{j=1}^m (V_{ij} - V_j^-)^2 \right]^{0.5}$$

v. Calculation of performance score (P_i)

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-}$$

The performance score is determined in the final phase, and the rank is inversely proportional to the performance score. The rank is then assigned to 27 iterations. Table 10 summarizes the TOPSIS optimization table for Surface roughness (Ra), Tool Wear and micro hardness of machined workpieces. The best conditions for turning EN-24 are at run number 22, which has a cutting speed of 100 m/min, a feed rate of 0.15 mm/rev, and a cut depth of 0.1mm [32].

Table 10

TOPSIS optimization table										
	Speed	Feed	DOC	Ra	TW	MH	Si+	Si-	Pi	Rank
1	40	0.1	0.1	1.348	0.064	486.4	0.0397	0.083	0.6767	5
2	40	0.1	0.3	1.349	0.157	523	0.0491	0.0549	0.5278	12
3	40	0.1	0.5	1.365	0.143	519.1	0.0474	0.0588	0.554	9
4	40	0.15	0.1	1.049	0.096	508.3	0.0267	0.0777	0.7444	3
5	40	0.15	0.3	1.382	0.185	528.4	0.0558	0.0462	0.4527	15
6	40	0.15	0.5	1.398	0.274	556	0.0775	0.0211	0.2139	23
7	40	0.2	0.1	1.478	0.121	512.6	0.0495	0.0644	0.5655	8
8	40	0.2	0.3	1.521	0.219	538.1	0.0681	0.0342	0.3346	20
9	40	0.2	0.5	1.659	0.304	564.7	0.0926	0.0073	0.073	25
10	70	0.1	0.1	1.093	0.074	502.9	0.0271	0.0832	0.7542	2
11	70	0.1	0.3	1.196	0.165	523.7	0.0448	0.0553	0.5524	10
12	70	0.1	0.5	1.204	0.241	545.1	0.0637	0.0352	0.3557	18
13	70	0.15	0.1	1.122	0.105	508.6	0.0311	0.0738	0.7034	4
14	70	0.15	0.3	1.328	0.198	529.8	0.0567	0.0434	0.4334	16
15	70	0.15	0.5	1.348	0.285	556.4	0.079	0.0204	0.2055	24
16	70	0.2	0.1	1.517	0.137	514.7	0.0532	0.0593	0.5271	13
17	70	0.2	0.3	1.452	0.224	538.5	0.0668	0.0337	0.335	19
18	70	0.2	0.5	1.578	0.318	574.7	0.0939	0.005	0.0503	27
19	100	0.1	0.1	0.557	0.183	503.4	0.0366	0.0714	0.6611	7
20	100	0.1	0.3	0.646	0.175	524.7	0.0347	0.0693	0.6665	6
21	100	0.1	0.5	0.896	0.269	553.8	0.0657	0.0423	0.3918	17
22	100	0.15	0.1	0.763	0.118	511.3	0.0198	0.0788	0.7994	1
23	100	0.15	0.3	0.974	0.204	533	0.0481	0.0514	0.5163	14
24	100	0.15	0.5	1.173	0.297	557.4	0.0784	0.0262	0.2506	22
25	100	0.2	0.1	1.354	0.146	519.1	0.0474	0.0581	0.5508	11
26	100	0.2	0.3	1.423	0.234	540.5	0.0682	0.0313	0.3144	21
27	100	0.2	0.5	1.541	0.327	579.7	0.0953	0.0059	0.0587	26

4. Conclusion

This study experimentally evaluated the performance of hybrid nanofluid-based MQL (HNFMQL) during the turning of EN-24 steel using varying nanoparticle concentrations (0.5 %, 1.0 %, and 1.5 %). Based on the experimental observations, the following conclusions are drawn:

1. The addition of Al₂O₃, MWCNT, and GnP nanoparticles significantly improved the physical properties of the base metalworking fluid—enhancing density, and dynamic viscosity—thereby improving heat transfer and lubrication behavior.
2. The 1.5 % hybrid nanofluid concentration consistently outperformed the lower concentrations for all response parameters, yielding the best combination of surface finish, minimal tool wear, and reduced micro-hardness.
3. The optimum surface finish was achieved at the lowest feed (0.1 mm/rev) and highest cutting speed (40 m/min) combination, confirming the synergy between fine feed and efficient MQL lubrication.
4. Application of 1.5 % hybrid nanofluid reduced surface roughness of the machined workpiece by approximately 17.3 % and 13.4 % compared to 0.5 % and 1.0 % concentrations, respectively.
5. The lowest tool-wear rate was recorded under mild machining conditions (40 m/min, 0.1 mm/rev, 0.1 mm DOC), with overall wear reduction of about 5 % and 3.1 % relative to the lower concentrations.
6. The observed reductions in surface roughness and flank wear at 1.5 wt% concentration indicate improved lubrication and heat dissipation at the tool–chip interface, which minimized adhesion-related wear and enhanced tool life and surface integrity.
7. The consistent improvement in machining performance suggests a synergistic interaction among Al₂O₃, MWCNT, and GnP nanoparticles, where MWCNTs contributed to thermal transport, while GnP and Al₂O₃ facilitated the formation of a stable lubricating film, leading to improved machining stability.

In summary, employing a 1.5 % Al₂O₃–MWCNT–GnP hybrid nanofluid under MQL conditions delivers a balanced combination of lubrication, cooling, and tribological benefits, leading to superior machinability and surface integrity of EN-24 steel. This concentration is thus recommended as the optimal formulation for sustainable precision machining applications.

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