

***Performance Assessment and Optimization of Bio-Modified SiO₂
Nanofluid Assisted CNC Turning of Mild Steel utilizing
Taguchi based GRA/TOPSIS***

Yared Selemon

Under the supervision of
Dr. Shishay Amare (Associate Professor)

*A Thesis Submitted to
the school of mechanical and industrial engineering in Partial Fulfillment of the Requirements
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MEKELLE UNIVERSITY

Ethiopian Institute of Technology-Mekelle

Faculty Of Mechanical and Industrial Engineering

Manufacturing Engineering Department

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Mekelle University
Ethiopian Institute of Technology-Mekelle
Faculty of Mechanical and Industrial Engineering
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Yared Selemon

Advisor

Dr. Shishay Amare, Associate professor

Mekelle, Tigray, Ethiopia

April 26

Thesis Acceptance Approval

This is to certify that Mr. Yared Selemon has covered all the comments and reflections forwarded by the internal and external evaluators and the chairperson at the thesis defense.

Members of the Examination Board

Dr. Belete Sirahbizu

Name of the External Evaluator



Signature

06/04/2026

Date

Dr. Goitom Desta

Name of the Internal Evaluator



Signature

20/04/2026

Date

Mr. Nebyat Gebrezgiher

Name of the Chairman



Signature

20/04/2026

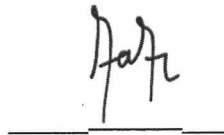
Date

Confirmation

Head of the Postgraduate and Research Office

Mrs. Fana Filli

Name of the Head



Signature

16/04/2026

Date

Faculty of Mechanical and Industrial Engineering (FoMIE)

Dr. Michael Gebreyesus

Name of the faculty Head



Signature

20/04/2026

Date

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Michael G/yesus (PhD)
Head Faculty of Mechanical &
Industrial Engineering

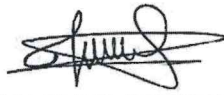


Declaration

This confirms that Yared Selemon has completed the thesis entitled "Performance Assessment and Optimization of Bio Modified SiO₂ Nanofluid Assisted CNC Turning of Mild Steel utilizing Taguchi based GRA/TOPSIS," which is submitted to the department of Manufacturing Engineering in partial fulfillment of the requirements for the master of science degree in Manufacturing Engineering. To the best of my knowledge, the work in this thesis has never been submitted before for any purpose at any university and other higher education establishment.

Yared Selemon

Student's Name



Signature

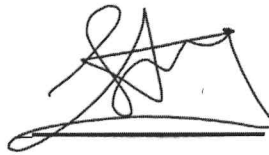
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I thus declare that I read this thesis work by Yared Selemon under my supervision, and the recommendation is that it be approved since, to the best of my knowledge, it met the requisite thesis criteria.

Dr. Shishay Amare

Advisor's name



Signature

6/6/2026

Date



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Abstract

The development of environmentally sustainable and performance-enhancing cutting fluids is increasingly vital in modern machining industries. This study experimentally investigates the performance of bio-modified nanofluid composed of nano-silica dispersed in sunflower oil with aloe vera extract as a base fluid. The study also aims to optimize CNC turning process parameters using Taguchi-based multi-response optimization methods. The performance of the developed nanofluid was compared to conventional water miscible cutting fluid during the machining of mild steel under minimum quantity lubrication (MQL) condition. The synthesized fluid at 0.25, 0.5, and 1 wt.% concentration of nano silica was characterized for viscosity, density, pH, and stability. Matrix of experimental trials was formed using an L9 Taguchi orthogonal array, and analysis of variance (ANOVA) and regression models were conducted. Two multi-response optimization methods were utilized, namely gray relational analysis (GRA) and technique for order preference by similarity to the ideal solution (TOPSIS). Surface roughness (R), material removal rate (MRR), and cutting temperature (CT) were measured as key machining performance indicators. Among the prepared nanofluids, the fluid containing 1 wt.% Nano silica showed the maximum viscosity at different temperatures, the highest density, the lowest stability, and a near-neutral pH. The experimental result showed that Surface Roughness reduction average of 10.28%, MRR increased by an average of 7.2%, and CT was 7.6% lower compared to the conventional. Such enhancements are attributed to the synergistic effects of nano silica and the base fluids thermal dissipation and lubricating characteristics. Both optimization methods identified 91 m/min cutting speed, 0.125 mm/rev feed, and 1 wt.% concentration of nano silica as optimal CNC turning parameters of mild steel. The findings demonstrate the potential of the proposed bio-modified nanofluid as an effective, eco-friendly alternative for sustainable and precision machining application.

Keywords: Silica, Nanofluid, Sunflower oil, Aloe vera, MQL, Taguchi, GRA, TOPSIS

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List of Abbreviations

ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
AV	Aloe vera
CC	Closeness Coefficient
CF	Cutting Fluid
Conv. F	Conventional Fluid
CNC	Computer numerical control
CT	Cutting Temperature
CS	Cutting Speed
D	Depth of Cut
DOE	Design of Experiment
E	Entropy
f	Feed
GRA	Grey Relational Analysis
GRC	Grey Relational Coefficient
GRG	Grey Relational Grade
MRO	Multi Response Optimization
MQL	Minimum Quantity Lubrication
MRR	Material Removal Rate
MWF	Metal Working Fluids
NF	Nano Fluid
pH	Power of Hydrogen
PLC	Private Limited Company

RPM	Rotation per Minute
S/N	Signal to Noise Ratio
SC	Silica Concentration
SEM	Scanning Electron microscopy
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
Wt.	Weight
WP	Workpiece

Chapter One

1. Introduction

1.1. Background

Machining processes play a vital role in modern manufacturing industries. Through machining processes, precise dimensions, complex geometries, and desirable surface quality can be achieved by removing parts from workpiece in the form of chips through the direct contact between cutting tools and the material. Among the types of machining processes, CNC (Computer Numerical Control) turning is a widely adopted machining process used to manufacture cylindrical and rotational components with high precision and consistency. It operates by rotating the workpiece while a cutting tool, controlled by a computer program, removes material to achieve the desired shape and dimensions. The process is preferred in modern manufacturing due to its ability to produce complex geometries with minimal human intervention, high repeatability, and improved productivity compared to conventional machining methods. CNC turning is commonly applied in industries such as automotive, aerospace, and general manufacturing, particularly when large quantities of identical parts are required with strict dimensional tolerances. It is especially suitable when accuracy, efficiency, and automation are critical. Material removal occurred primarily through plastic deformation at the cutting area. Nearly 99% of mechanical energy is supplied to the cutting tool, and such energies are converted into thermal and friction [1] [2] [3].

Machining of low-carbon (mild) steel is extensively carried out in manufacturing industries, particularly in the production of engine and automotive components, structural parts, and general engineering applications. Low-carbon steel, typically containing less than 0.25% carbon, is widely used due to its good ductility, toughness, weldability, and relatively low cost. These properties make it easy to form and machine; however, its relatively low hardness and strength can sometimes lead to issues such as built-up edge (BUE) formation during cutting, which affects surface finish and tool performance [1], [4]. The fabrication of low-carbon steel components commonly employs High-Speed Steel (HSS) cutting tools because of their affordability and wide availability. HSS tools can be easily ground into complex geometries and provide adequate hardness, toughness, and thermal resistance for machining operations. Although carbide tools offer higher wear resistance and cutting speed capability, they are more brittle and prone to fracture under certain conditions.

Therefore, HSS tools remain a practical and economical choice for machining low-carbon steel in many industrial applications [4] [5] [6].

During the operations, a significant amount of heat is created, which adversely affects the surface quality of the workpiece and tool life. In addition, it also increases cutting temperature, causing excessive energy consumption, most of which is eventually removed as waste heat to the atmosphere. To mitigate these effects, the utilization of cutting fluid is usually mandatory. Cutting fluids help minimize heat generation and surface friction, thereby improving surface quality, increasing tool life, and lowering consumption of energy. Typically, cutting fluids consist of a mixture of surfactants, anti-corrosive agents, lubricants, biocides, oils, detergents, and other potentially harmful ingredients. As a result of the contact between the workpiece and working tool, the use of cutting fluids plays a significant role in improving machining effectiveness and ensuring operational stability [7], [8], [9].

Historically, cold water was used by manufacturers to reduce the cutting zone temperature. This operation resulted in the better removal of chips as well as temperature reduction, and a 30% improved in productivity was reported. However, adequate lubrication was essential to minimize friction between contacting parts. Lubricants, whether in solid or liquid form, are used for many applications where a greasing action is required. Mineral oils (MOs) known for their good lubricating characteristics, were used to lubricate workpieces and tools. When mixed with different additives, mineral-oil-based cutting fluids provide both greater lubricating performance and effective cooling, making them widely applied in machining processes [10], [11], [12].

According to a study by several American institutes, states that approximately 60% of industries are spending 20% more cost on their coolants and lubricants in a machining operation than on the sharp tool being utilized for removing a part. This high cost has prompted researchers and engineers to explore optional and more effective cooling and lubrication strategies. These explorations have led to innovations like cryogenic cooling, minimal quantity lubrication, biodegradable fluids, and solid lubricant suspensions in fluid [13]. Cutting fluids typically contribute to 10-17% of the total production cost, as indicated in the pie chart in Fig. below. Similarly, optimizing the application of these fluids has become a critical consideration for minimizing overall manufacturing costs in industries [9], [12].

Micro and nanofluids are recently emerging solutions for cooling and lubrication that can be explained as the liquids containing micro or nanoparticles, which has tremendous thermal and

rheological performance compared to conventional once [14], [15]. Because of these, they have become increasingly attractive for industrial applications, such as machining, automotive, electronics, and biomedical industries. During machining, they contribute to improving cutting efficiency by reducing friction at the workpiece-tool interface, decreasing cutting temperature (CT), maximizing tool lifespan and manufacturing higher surface integrity. Furthermore, mixing nanoparticles in vegetable oils which are naturally eco-friendly, boosts their lubricating property, making the fluids highly effective for the minimum quantity lubrication (MQL) method [16].

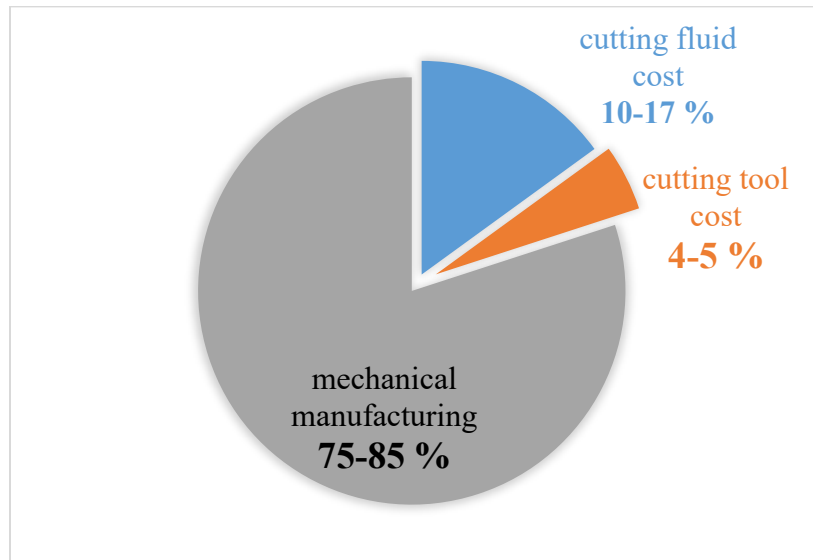


Figure 1:1 Manufacturing costs (Nazma Sultana et al. 2019 [9], Kui et al. 2022 [12])

In the past few years, significant effort has been made to conduct further research on studying and improving machining performance, focusing on the applications of MQL, and the utilization of vegetable oil-based cooling and lubricating fluids in the machining of different materials [10].

To increase the qualities of a machining fluid, different additives and supplementary agents are blended with the primary lubricant. While these modified fluids play a significant role in machining parts, they also have risks to both environmental and human health when they are not properly handled during and after use. The global emphasis on environmental sustainability and minimizing workplace safety led the researchers to explore alternative lubricants [17].

Over the last two decades, concerns about environmental protection and occupational health have led to the rise tighter regulations on the utilization of certain chemical components found in metal working fluids. Regulations, such as “The European Union REACH Regulation for Chemicals: Law and Practice. "Prevention of Metalworking Fluid Pollution: Environmentally Conscious

Manufacturing at the Machine Tool" Skerlos, S. J. (2007). Prevention of Metalworking Fluid Pollution: Environmentally Conscious Manufacturing at the Machine Tool. In *Environmentally Conscious Manufacturing* (pp. 95–122). John Wiley & Sons, Inc. In addition, recent regulations on environmental problems, such as standards like ISO 14000, reflect a global trend towards stricter environmental guidelines, encouraging organizations to adopt greener manufacturing approaches.

To meet the challenging demand of cooling and lubrication in machining workshops with Nano fluid which is an innovative idea in which Micro/Nano-sized particles are dispersed in the base vegetable oil liquid.

1.2. Problem Statement

CNC turning is one of the most widely used machining processes in modern manufacturing due to its high precision, repeatability, and ability to produce complex geometries with minimal human intervention. Machining with low carbon steel materials is often carried out in manufacturing processes. However, the process is significantly affected by cutting conditions such as heat generation, tool wear, and friction at the tool workpiece interface, which directly influence surface quality and material removal rate. Conventional cutting fluids have been employed to mitigate these challenges, but they often pose environmental and health concerns while offering limited performance under severe machining conditions. In recent years, nanofluids, particularly those incorporating nanoparticles such as SiO_2 have shown promising potential in enhancing lubrication and heat transfer characteristics. Despite these advancements, limited studies have explored bio-based nanofluids derived from sustainable materials like sunflower oil and aloe vera extract, especially in CNC turning applications of mild steel. Moreover, the comparative effectiveness of multi-response optimization techniques such as Gray Relational Analysis (GRA) and TOPSIS in such contexts remains insufficiently investigated, thereby justifying the need for the present study.

1.3. Objective of The Research

1.3.1. General Objective

- ✓ To experimentally investigate and optimize the machining performance of CNC turning of mild steel using bio-modified SiO₂ nanofluid through Taguchi-based GRA and TOPSIS methods.

1.3.2. Specific Objective

- ✓ To prepare an eco-friendly machining nanofluid by dispersing the nano-sized silica particles into an aloe Vera oil base fluid using appropriate mixing techniques to ensure homogenous distribution and stability.
- ✓ To experimentally characterize the thermophysical properties of the prepared nanoparticle-dispersed cutting fluid (nanofluid).
- ✓ To evaluate the performance of the proposed cutting fluid by comparing it with conventional fluid using performance metrics (material removal rate, surface roughness, and cutting temperature).
- ✓ To optimize the turning process parameters during nanofluid-assisted machining of mild steel using multi-objective optimization methods
- ✓ To study the effect of the machining factors on surface roughness, cutting temperature, and material removal rate

1.4. Scope of the Research

The primary scope of this thesis is a general investigation of the application of nanofluids in machining operations. It includes conducting an in-depth literature review, performing chemical composition analysis of the mild steel workpiece, preparing and characterizing the sample nanofluid, and conducting controlled turning experiments. The aim of the study is to analyze the performance of the prepared fluids on machining characteristics, such as surface roughness, material removal rate, and cutting temperature, compared with conventional fluids. Furthermore, the research involves analyzing the significance of various machining parameters, identifying the optimal parameter combinations using statistical tools and methods, and finally drawing conclusions and proposing recommendations for application.

1.5. Significance of The Research

After completing the overall experimental work on the experimental investigation of nano cutting fluid, the significance of the thesis will provide an alternative biodegradable cutting fluid with potential industrial benefits of improved cutting fluid effectiveness, such as extended tool lifespan, reduced energy consumption, and enhanced surface quality. Also supports sustainable manufacturing, the use of eco-friendly nanofluid. Finally, it opens a new research area on sustainable manufacturing using bio-modified nanofluids.

1.6. Limitation of Study

The research focuses only on mild steel material, meaning the results may not be directly applicable to harder or softer materials like stainless steel or aluminum. The study is limited to specific parameters, cutting speed, silica concentration, and feed, which may not fully represent all turning industrial applications. Precision in measuring instruments (roughness testers, temperature, digital balance, pH, and viscometer) may introduce minor measurement errors.

1.7. Organization of The Thesis

The thesis is divided into five different chapters. Chapter one begins with an introduction and background of the study, which describes the main facts and importance of the research field. The research objective, scope of the research, and significance of the research are all shown in the first chapter sub-sections. Then chapter two is a literature review, which includes an overview of prior related research on the research problem, as well as its strengths and flaws, as well as a rationale for the research - what is known/what has been done by others, and why the research is still needed. The third chapter discusses research methodologies and materials, such as the design of experiments (DOE) matrix, experimental setup, and data gathering and analysis techniques. The fourth chapter reports and discusses the key findings of the investigation, the experimental analysis, and the interpretation of the DOE results. Finally, chapter five discusses the study's conclusion, recommendations, and future research directions.

Chapter Two

2. Literature Review

2.1. Machining Fundamentals

Machining is a subtractive manufacturing technique where excess material is cut away from a workpiece using sharp tools to obtain the required geometries and surface quality. Among various machining operations, turning, particularly CNC turning, is commonly applied in manufacturing industries because of its efficiency, precision, and versatility in shaping cylindrical components [1]. This operation uses a single-point sharp tool to remove part from a rotating cylindrical workpiece. Three critical parameters influence the outcome of turning: cutting speed (V), feed rate (f), and depth of cut (d). These parameters affect tool wear, surface roughness, cutting temperature, and material removal rate (MRR). The interaction between the workpiece and the cutting tool generates plastic deformation and intense friction in the shear zone, which in turn leads to high localized heat generation. Almost all the heat produced while metal cutting is concentrated in the tool-chip interface, potentially degrading the tool material, workpiece surface, and dimensional accuracy.

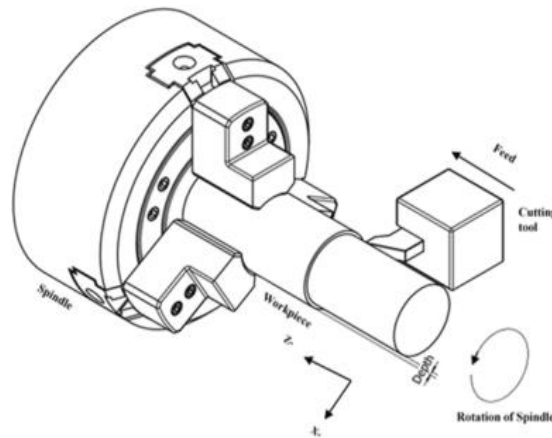


Figure 2:1 Lathe straight turning of a metal bar [1]

To counteract these issues, cutting fluids are introduced to perform two main roles: cooling and lubrication. Cooling reduces the heat load in the cutting region, while lubrication minimizes friction, thus improving surface quality and tool life. Traditional machining fluids, although effective, are increasingly inspected for their environmental and health impacts, leading to a shift toward bio-based and nano-enhanced alternatives. In the past few years, the use of nanoparticle-

enriched machining fluids in turning processes has gained attraction because of their enhanced thermal conductivity and tribological behavior. These fluids reduce the coefficient of friction, dissipate heat efficiently, and protect the cutting tool and workpiece surfaces through mechanisms including rolling action, self-repairing (mending) behavior, and shielding film formation. The effectiveness of nanofluids in machining is particularly relevant in the context of Minimum Quantity Lubrication (MQL), where small amounts of high-performance fluids are applied to achieve sustainable and efficient machining.

2.2. Turning of Mild Steel

This study focuses on the turning of mild steel (St 37-2), a commonly used low-carbon alloy, using a newly developed nano cutting fluid composed of silicon dioxide (SiO_2) nanoparticles dispersed in aloe vera-enriched sunflower oil. The objective is to enhance machining performance, specifically MRR, surface quality, and the cutting temperature through optimized process control parameters.

The optimization of factors for turning operations on commercial mild steel utilizing the Taguchi approach has been made. The findings demonstrate that the Taguchi method is effective in systematically improving machining performance, with enhancements in MRR and surface finish [18]. Research focuses on optimizing machining parameters using surface roughness as the key performance metric. Regression analysis (RA) was applied to model the data, and Particle Swarm Optimization (PSO) identified optimal parameters for reducing surface roughness. The PSO results were validated against experimental data, confirming the model's adequacy for achieving smoother surfaces [19]. Also, a study applied a Multi-Criteria Decision-Making (MCDM) approach to optimize a turning process using the Taguchi method. Nine experimental trials were performed by altering cutting speed, feed, depth of cut, and nose radius. Cutting forces (F_x , F_y , F_z) and Material Removal Rate (MRR) were measured. The Entropy weighting Method was utilized to allocate weights, and eight MCDM methods were applied to identify the optimal setup minimizing cutting forces while maximizing MRR. Most methods agreed on the best experiment, and a new MCDM method was proposed for future studies [20].

Another study aims to optimize machining parameters using performance metrics like tool damage and material removal rate (MRR) for AISI 1018 material using the Taguchi approach in turning. Spindle speed, feed, depth of cut, and type of working fluid were varied across three levels. Two

different vegetable-based fluids and a semi-synthetic fluid were compared for sustainable machining. Taguchi's L9 orthogonal array and ANOVA were applied for optimization, and results were validated through confirmation tests [21]. [22] Researchers addressed heat generation in machining. They optimized air-assisted turning parameters, assessing cutting speed, feed rate, and tool overhanging on surface roughness (Ra) and productivity (MRR). The study found that increasing cutting speed improved surface finish, while higher feed rates and tool overhang negatively impacted Ra. A genetic algorithm (GA) was used for multi-response optimization, identifying four optimal parameter sets to balance MRR and Ra, contributing to sustainable machining practices. [5] The study analyzed the influence of tool geometry on surface roughness while machining low-carbon steel (ST-37) using HSS tools. Parameters such as side cutting edge angle, side rake angle, and nose radius were varied, along with machining depth, speed, and feed level. Tool wear and surface roughness were analyzed using Taguchi and Grey Relational Analysis (GRA) and ANOVA. The optimal setup included a 1 mm depth of cut, 17.42 m/min speed, 0.05 mm/rev feed, and a 0 mm nose radius. ANOVA results highlighted spindle speed, chip angle, and tool tip angle as key factors for minimizing wear and improving surface finish.

Overall, these studies highlight different statistical tools and methods to perform optimization of process parameters and also the importance of machining parameter optimization in improving cutting performance, sustainability, and surface integrity of turning of different materials, offering insights for industrial applications.

2.3. Machining Fluids

The use of machining fluids dates back to 1894, when F. Taylor noted that cutting speed could rise to approximately 33% through the usage of a large amount of water in the cutting region, although this did not help for the minimization of tool wear [11]. Brinksmeier defines machining fluids as fluids that are supplied to a manufacturing process to increase productivity by providing lubrication and cooling effects [8]. The application of these fluids serves two primary functions in machining. The first is to provide sufficient cooling, especially at high spindle speeds where the cutting region temperatures tend to increase significantly. The second is to make lubrication at relatively low cutting speeds where cooling is insignificant. MWFs are used to meet multiple objectives, including reducing friction between the cutting tool and the workpiece, extending tool

life, enhancing surface finish, facilitating chip removal, and preventing overheating of the tool, workpiece, and machine [9] [12] [11].

In the machining process, two primary types of cutting fluids are employed, namely oil-based and water-based fluids, as indicated in *Figure 2:2*. These oil-based fluids (vegetable, mineral, animal, synthetic) are used in low-speed machining for lubrication, emulsions (water-oil mixtures) for high-speed operations to enhance cooling and reduce oxidation, semi-synthetics combining small oil particles in water for balanced cooling and lubrication, and synthetics, fully chemical-based fluids offering excellent cooling but limited lubrication. Increasingly, environmental sustainability has become a critical concern in the machining industries.

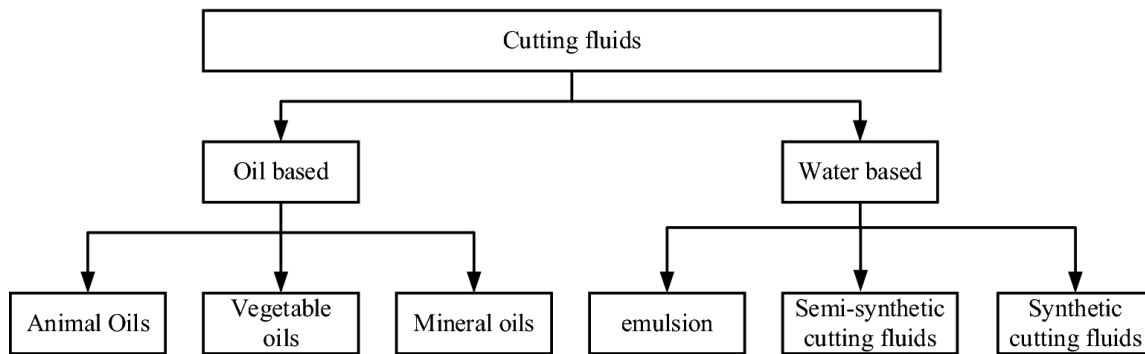


Figure 2:2 Classification of conventional metal cutting fluid according to formulation [8]

2.3.1. Vegetable Oil-Based Cutting Fluids

Recent research has shown that bio-based machining fluids offer better lubrication and maintain stable viscosity at high temperatures better than mineral oil-based manufacturing fluids. The vegetable oil cutting fluids are derived from natural plant sources and present a sustainable and environmentally friendly alternative. Vegetable oils are nontoxic, biodegradable, and have a good lubrication effect. Additionally, their higher viscosity compared to mineral oils makes them capable of reducing consumption during machining operations. To possess a combined effect, additives such as antioxidants, corrosion inhibitors, surfactants, and anti-wear agents can also be mixed [10] [23].

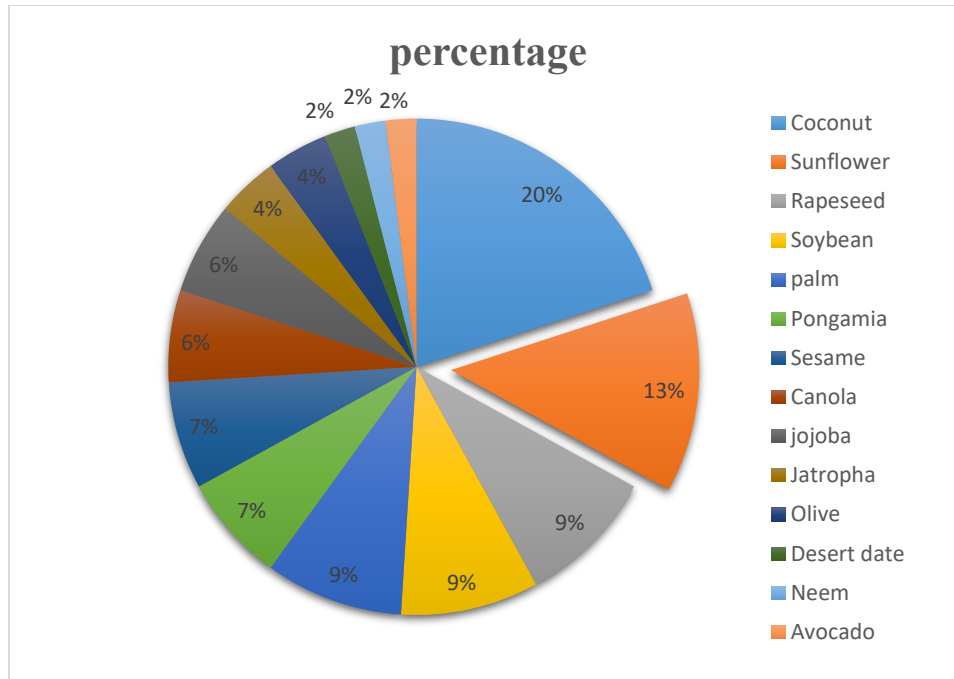


Figure 2:3 Common vegetable oils used for preparing nanofluids [24]

[25] A research investigated the use of aloe vera oil using the Minimum Quantity Lubrication (MQL) method for turning M2 steel. The study revealed that aloe vera oil significantly enhanced surface roughness and improved tool life when compared with mineral oil, highlighting its suitability for green machining practices. Researchers evaluated the employment of groundnut and soybean oils in the milling of aluminum alloys and mild steel. Results from surface morphology analysis using optical and atomic force microscopy ensure the oil's effectiveness in surface finish and hardness, but slightly increased cutting forces [26]. A paper compared vegetable-oil cutting fluids with mineral-oil fluids for turning AISI 1050 steel. From microbial contamination testing, it was observed that vegetable-based emulsions had better microbial resistance than mineral oils. The most favorable result was observed with respect to machining temperature and surface quality, while tool life was maximized with vegetable-based emulsions [27]. [28] A study examined neem seed oil as a machining lubricant for mild steel, utilizing the Taguchi approach. Results showed that rotating speed, fluid flow speed, and air pressure significantly influenced chip formation and thermal stability, establishing Neem oil as an effective bio-lubricant. [29] assessed castor seed oil-based turning fluid during the machining of AISI 1020 mild steel. Using Taguchi and GRA, the study found that castor oil performed comparably to mineral oils, with reduced environmental impact and optimized process parameters. Similarly, [30] formulated a new machining fluid by

blending aloe vera extract with coconut oil and used Taguchi optimization to enhance the turning of EN-31 steel. The blend significantly improves productivity (MRR), surface finish, and tool life under optimal turning speed and feed conditions.

All the above reviewed studies show the increasing adoption of vegetable oils and biodegradable lubricants in machining industries, for improving surface quality, tool working lifespan, minimizing force while maintaining environmental friendliness. Various optimization systems, involving Taguchi, GRA, PSW, GA, and Behnken's design, have been successfully applied to find optimal cutting parameters, further enhancing performance.

2.3.2. Mineral Oil-Based Cutting Fluids

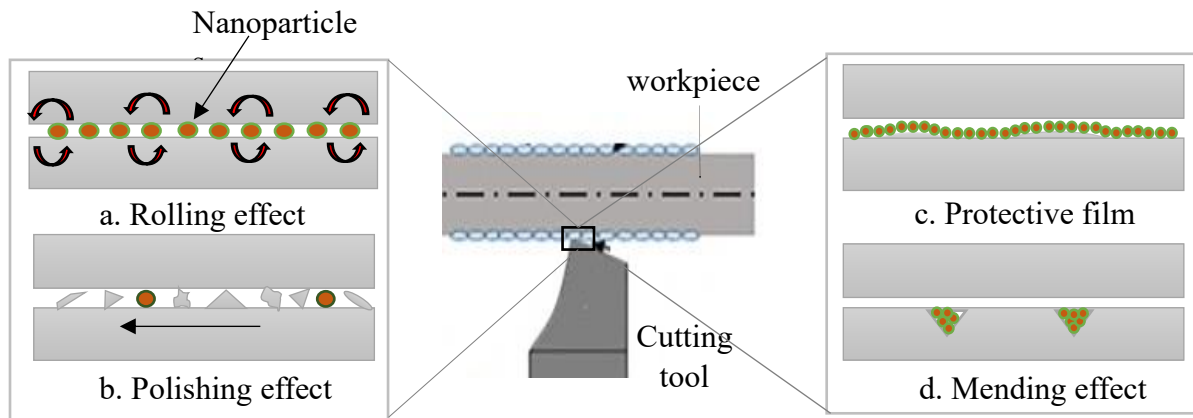
Mineral oils are commonly used as machining fluids in cutting operations because of their good lubrication characteristics, which help minimize friction, heat, and tool wear. Mineral oils usually use additives such as extreme pressure agents, antiwear compounds, and corrosion inhibitors to increase their performance. [31] compared bio-based cutting fluid (BCF) with mineral oil (MO) in the machining of AISI H-13 steel, applying a MQL system. Results showed BCF notable minimization in cutting force, feed force, friction, and surface roughness owing to its enhanced lubrication capability. Similarly, [32] formulated a stable, eco-friendly machining fluid using non-edible vegetable oil. Compared to traditional fluids, it lowered the cutting force, improved surface roughness, and reduced tool damage. ANOVA revealed that conventional mineral oil working fluid type strongly influenced surface roughness (69.15%) and tool damage (56.85%), confirming its performance and sustainability advantages.

Regardless of their effectiveness, these oils have significant environmental and health drawbacks. Researchers ensured that they are non-biodegradable, can cause skin irritation, and are carcinogenic. Careless removal of these oils also contributes to environmental pollution, resulting in the development of more sustainable machining fluid alternatives [27], [31], [32].

2.3.3. Micro/Nano Cutting Fluids

Micro or nanofluids have emerged as optional solutions for cooling and lubrication, consisting of fluids containing suspended micro or nano-sized particles that exhibit greater thermal and tribological properties. Therefore, they improve machining performance by minimizing the coefficient of friction, lowering cutting temperature (CT), increasing tool lifespan, and producing

better surface integrity [15]. Also, according to many research papers, nanofluids seem to assist during the machining process, as illustrated in the figure below.



(a) in rolling effect, (b) polishing effect, (c) Protective film effect, (d) in mending effect

Figure 2:4 Mechanisms of nanoparticle seem to assist in machining processes [24]

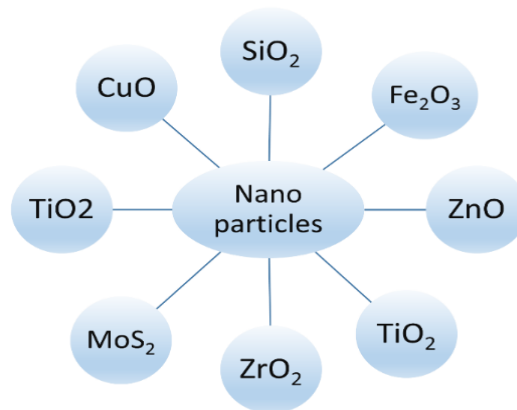


Figure 2:5 Widely used nanoparticles for the preparation of nanofluids for machining

[33] Research examined enhanced straight ester sunflower oil (SESO) by mixing it with micro and nano-scale powder particles, particularly spherical TiO_2 , rod-shaped ZnO , and MoS_2 . The tribological testing showed that ZnO improved the coefficient of friction and wear scar diameter, highlighting the potential of a hybrid particle-enhanced nano lubricant. Also, a paper studies reinforced soybean, sunflower, and corn oils blended with SiO_2 nanoparticles to find alternative high-performance fluids. The results revealed that sunflower oil mixed with 0.25 wt% of SiO_2 nano powder increased load carrying capacity by 60%, showing the effect of the modified fluids for potentially effective machining [4]. [34] Also, the influence of the proportion and particle size of TiO_2 nanoparticles in the base fluid during turning operations was evaluated. Their findings

indicated that increasing particle size from 10 nm to 50 nm reduced tool wear by up to 46.2%, suggesting that particle size optimization is critical to tool life extension. [14] compared the cutting performance of Al_2O_3 , MoS_2 , and graphite-based nanofluids under MQL when turning Inconel-800. Among the tested formulations, graphite-based vegetable oil nanofluids showed better lubrication and cooling efficiency, especially at higher speeds, making them effective for difficult-to-machine alloys. Nanofluid prepared using SiO_2 and TiO_2 nanoparticles at sunflower oil as base fluid was examined for pin-on-disc tribological test, confirming notable reduction in coefficient of friction, 93.7% using TiO_2 and 77.7% using SiO_2 , and reduction in wear volume, ensuring the viability of nano powder modified sunflower oil as effective lubricant [16]. [35] found that silica and copper oxide particles improved drilling performance. SO_2 minimized fluid loss by 31% in NDDF, while copper oxide lowered viscosity by 24% in BDF. Then the optimal results were observed at a concentration of 0.5%, increasing rheology control.

[36] Researchers formulated SiO_2 -based nanofluids at 0.5%, 1.0%, and 1.5% concentrations and tested them in CNC milling of AL6061-T6. Results indicated that the 1.5% wt. concentration yielded the least surface roughness and cutting temperature, indicating better lubrication and heat dissipation. An experiment applied SiO_2 nanofluid at three concentrations in MQL-assisted CNC turning of AL319. The 1.5% SiO_2 nanofluid outperformed conventional fluids, producing the lowest cutting temperature of 28.4 °C and a better surface finish of 1.089 μm ; also, tool wear was less affected because of small experimental runs [37]. [38] Another research tested boric acid nanoparticles in canola oil for MQL machining of EN19 steel, and results observed that increasing concentration continuously reduced cutting force, temperature, and roughness of the surface, ensuring the feasibility of the prepared fluid. [39] A paper evaluates the tribological performance using pin-on-disc tests of a fluid synthesized from mixed SiO_2 , Al_2O_3 , and TiO_2 nanoparticles with SN 500 base oil. It is observed that a significant improvement in friction and wear reduction. The optimal proportion of the nanoparticles was determined utilizing Taguchi and GRA, indicating that hybrid mixing can synergistically enhance lubricant performance. [40] Another study developed an ecofriendly fluid by dispersing ZnO nanoparticles in sunflower oil during the milling of mild steel. The study found that 1.5% of ZnO concentration delivers good MRR and SR, as analyzed using the RSM method. [41] Sunflower oil with varying concentrations of alumina (Al_2O_3) nanoparticles is also used to conduct machining tests on Hastelloy C-276. A 0.6 vol% concentration yielded the best results, with reductions in SR and tool damage by 73.31% and

82.14%, and also demonstrated lower energy consumption and carbon emissions, affirming its sustainability advantages. [42] analyzed the performance of SiO₂ nano-particles in sunflower oil during MQL turning of AISI 304 stainless steel. Testing showed that the 0.5% NanoMQL concentration achieved superior outcomes in machining temperature and tool damage reduction. The feed rate influenced surface roughness most significantly, while the cooling method had the greatest impact on tool performance.

Silicon dioxide (SiO₂) nano-particles are brittle, hard, cost-effective, and widely available in nanoscale sizes (5–100 nm). Their high hardness (Vickers hardness ~1000 kgf/mm²) and chemical stability make them suitable for use in nanofluids. In machining, SiO₂ acts as rolling/sliding elements at the tool–chip contact, lowering friction, cutting forces, temperature, tool wear, and surface roughness. Despite that, SiO₂ nanofluids show enhanced effectiveness in different base fluids; limited research is presented on their application in turning of mild steel using biomodified vegetable oil as a base liquid. This research tries to investigate the performance of such formulations.

2.4. Cooling and Lubricating Techniques

In addition to the different types of fluids, extensive studies have been conducted focused on the mechanism of how to apply them effectively, and are now available to manufacturers. The choice of an appropriate cooling and lubrication technique can depend on factors such as the workpiece material, cutting tool properties, and processing conditions.

The elimination of cutting fluids using dry machining techniques results in a minimization of the production costs and ecological impacts. However, dry cutting presents some problems, such as excessive tool damage and lower surface integrity. For instance, during end milling of titanium alloy material, localized flank deterioration was observed due to excessive thermal generation [7], [9], [12]. One of the common cooling and lubrication systems used in most of machining operations is the utilization of flood coolant. Typical flow rates vary depending on the processes, ranging between 10 L/min (3 gal/min) for single-point machining tools and 225 L/min (60 gal/min) per cutter for multiple-tooth cutters. Studies have shown that it improves tool life, surface finish, and chip evacuation [9], [12], [27]. Despite these advantages, flood cooling involves high fluid consumption, environmental concerns, and health risks, motivating research into more sustainable machining alternatives.

Mist cooling is specifically effective when utilizing water-based machining fluids at air pressures between 70 and 600 kPa (10 to 80 psi). However, its cooling capacity is very low [43]. Generally, mist lubrication and cooling aren't as effective as flood cooling, but it could apply the cutting fluid for unreachable areas that traditional or existing flood cooling cannot reach [9], [11]. By ensuring higher penetration of the fluid into the machining region, High-Pressure Cooling HPC efficiently minimizes both cutting temperature and machining forces, thereby reducing tool damage compared to traditional flood cooling and dry cutting [9] [11]. HPC can supply an optional cooling during machining, especially during the process of turning, where the coolants can be provided through a specialized insert in tool with integrated nozzles [12].

Minimum Quantity Lubrication (MQL) has been extensively studied for its ability to reduce cutting temperature, friction, and tool wear while using minimal fluid. [31] reported that MQL reduced cutting temperature by up to 35% and improved tool life by 28% compared to dry machining in the turning of low-carbon steels. [44] Another study demonstrated that sunflower oil-based nanofluid-assisted MQL decreased surface roughness of mild steel from 2.8 μm (dry) to 1.5 μm while extending tool life by approximately 32%. Similarly, [13] observed that micro- and nanofluid MQL reduced cutting forces by 15–25%, highlighting enhanced lubrication efficiency and energy savings. These findings confirm that MQL, especially when combined with environmentally friendly or nanoparticle-enhanced fluids, provides a highly effective and sustainable alternative to conventional flood or mist cooling. Another advanced cooling technique that employs coolants like liquid nitrogen (LN₂) at -196°C or carbon dioxide (CO₂) or dry ice at -78.5°C is a cryogenic cooling system. It is useful for hard machining, reducing white layer regions, and ensuring finer grain size. It helps to reduce cutting surface temperature, cutting force, and SR when machining materials like Ni-based Hastelloy C-2764. It can increase the tool working time and chip brittleness [9], [11], [8], [7]. It has limitations, such as a high-cost machining setup is required.

Among cooling and lubrication techniques, dry cutting reduces cost and environmental impact but causes high tool wear and poor surface quality, while flood and mist cooling improve tool life and surface finish at the cost of high fluid consumption and ecological concerns. HPC enhances cooling and reduces cutting forces but requires specialized setups. In contrast, MQL has emerged as an effective and sustainable method, significantly lowering cutting temperature, forces, and surface

roughness. However, limited studies have applied bio-based nanofluid-assisted MQL specifically for CNC turning of mild steel, highlighting a clear research gap.

2.5. Summary and Gaps Identified in The Literature Review

Earlier findings have shown that the performance of nanofluids in improving cutting efficiency, particularly in reducing friction, lowering cutting temperatures, and improving surface roughness. Research on silica (SiO_2) nanoparticles has shown their ability to modify the thermal and lubricating characteristics of cutting fluids, while aloe vera has been explored for its bio-based lubricating and dispersing properties. However, no studies have studied the effect of SiO_2 nanoparticles and aloe vera in vegetable oil-based cutting fluids combined in machining applications. There are also limited studies on the utilization of various multi-objective optimization approaches, particularly when analyzing the performance of such fluids in MQL systems. This allows for cross verification, minimizes bias, and produces more reliable results. Additionally, the application of those machining liquids using the MQL system for turning of mild steel compared with the conventional one is still unassessed.

This thesis aims to bridge these previous research gaps by experimentally assessing the performance of SiO_2 particles dispersed in sunflower oil- aloe vera based fluid, evaluating their impact on productivity, SR, and cutting temperature in the machining of mild steel while promoting sustainability and applying different optimization methods.

Chapter Three

3. Materials and Methodology

3.1. Materials

3.1.1. Silicon Dioxide (SiO₂) Nanoparticle

Many types of nanoparticles have been used as solid suspensions in the synthesis of nanofluids by researchers to examine their influence on the machining effectiveness. It is well known that silicon dioxide (SiO₂) nanoparticles are a brittle and hard material, and are inexpensive and easily found on the market. This particle has very moderate mechanical characteristics, especially in terms of hardness, and can be found in a small size range from 1 to 100 nanometers. Thus, the SiO₂ nano powder particles in base fluid, typically oil, would act as both sliding bearings and rolling at the workpiece-tool and tool-chip interface [10][6]. This enables the preparation of nanofluids with higher machining performance.

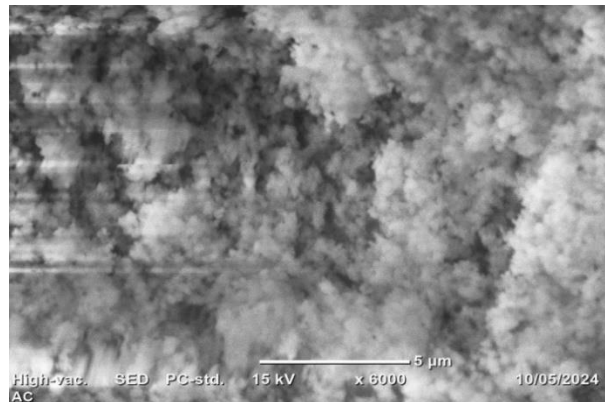


Figure 3:1 a. silicon dioxide nano powder; b. SEM image of the SiO₂ Nanoparticle

In this research, Amorphous silica SiO₂ Nano powder, having an average size of 90 nm, was prepared by researchers **Negash et al. 2025** [45], synthesized through the sol-gel method, has been purchased for the nanofluid preparation.

Table 3.1 Characteristics of silica nanoparticles

Characteristics	SiO ₂ nanoparticle
Structure	Amorphous
Density (g/cm ³)	2.2
Purity	98.98%
Color	White

Average Size

90 nm

3.1.2. Aloe Vera Fluid

Traditional cutting fluids often contain chemicals that are harmful to the environment. Aloe vera is a biodegradable, natural substance, contributing to eco-friendly alternative that reduces the ecological footprint of manufacturing processes. Studies have shown that Aloe Vera barley, mixed with vegetable oil-based machining fluids, provides an environmentally safe alternative to commercial lubricants in machining with enhanced surface quality and reduced tool damage [25], [30], [46]. Additionally, studies [47] [48] Highlighted Aloe Vera gel's antioxidant properties to mild steel material, which helps prevent oxidation of the material and even the cutting tool.

Generally, aloe vera is natural, cheaper, and easily available when compared to many liquids, nontoxic and hypoallergenic, making it safer for machinists in terms of skin contact and inhalation. They also have natural antimicrobial properties that can mitigate the growth of fungal and bacterial colonies. Thus, supports prolonging the life of the prepared fluids by preventing microbial contamination, a common challenge with water based cutting fluids. In this investigation, aloe vera extract is used to prepare the base liquid by systematically mixing with vegetable oil.

Table 3.2 Thermophysical properties of aloe vera gel

Properties of Aloe vera gel	Measured value
Density (g/cm ³)	0.93
Viscosity cst at 40 °C	40
Flash point	350
PH	5.4
Color	Color less



Figure 3:3 Commercially available edible sunflower oil

In this experimental investigation, Sunflower oil is utilized to mix with aloe vera extract because of its higher and unique capacity over other vegetable and mineral oils for preparing nanofluids, particularly in machining applications.

3.1.4. Conventional Fluid

In this research, a traditional cutting fluid, Aquatex 3180 water-soluble oil, made in Egypt, was employed as a turning fluid for comparison with the proposed nanofluid. This liquid is milky white when added to water, forming a stable emulsion that enhances heat dissipation and lowers tool deterioration. These fluids are high-performance coolants usually applicable in machining workshops because of their effectiveness in various machining applications. The selection of this conventional fluid enables a clear comparison against the proposed machining lubricant.

Table 3.4 Characteristics of conventional fluid

Characteristics of the conventional fluid	
Grade	Metal Cutting
Country of Origin	Made in Egypt
Physical state -	Liquid
Odour -	Mild
PH -	9.8 in 5 % emulsion
Solubility in water -	Completely soluble



Figure 3:4 Conventional cutting fluid (water-soluble oil)

3.1.5. Workpiece Material

Material used for the performance assessment of the proposed fluid in this research study is Mild steel St 37-2, which is equivalent but not the same as the properties of ASTM A36 and ISO Fe360B, also well known as low-carbon steel. It is a mostly applicable material in engineering and manufacturing because of its moderate mechanical behavior, affordability, and versatility. It usually consists of 0.05 – 0.25% of carbon, which provides it with good ductility, weldability, and machinability while maintaining moderate strength. The lower carbon content within these materials enables them to be less brittle and easier to shape. These materials are commonly used in applications like agricultural tools, structural, and even machine elements, making them a fundamental material in industrial and construction projects [5].

A total of 18 sample pieces have been prepared for both the experimental group, each piece having a geometry of 3 cm in diameter and 14 cm length, with little variety in length only, of which only 80 mm of the length is being machined, as indicated in the *Figure 3:5*. Due to its defects presented on the surface, the samples undergo a single turning operation to solve the variation that may arise. The detailed information of the mechanical characteristics and elemental composition of mild steel St 37-2 is provided in *Table 3.5* and *Table 3.6*. Results are from Mesfin Industrial Engineering Spectrometric Test Lab and are indicated in the Appendix.

Table 3.5 Properties of St 37-2 low-carbon Mild Steel Specimen

Density	Tensile strength	Yield strength	density	Elongation (A5)	Young modulus	Thermal Conductivity	Hardness (Brinell)
7870 Kg/m ³	360-510 MP	>235 MP	7.85 g/cm ³	≥ 25%	205 Gpa	54 W/m·K	120–160 HB

Table 3.6 Chemical Composition of St 37-2 low carbon Mild Steel Specimen

Elements	C	Mn	Si	Cr	Cu	Ni	Zn	Fe
Percentage Composition	0.079	0.222	0.114	0.034	0.194	0.028		98.8

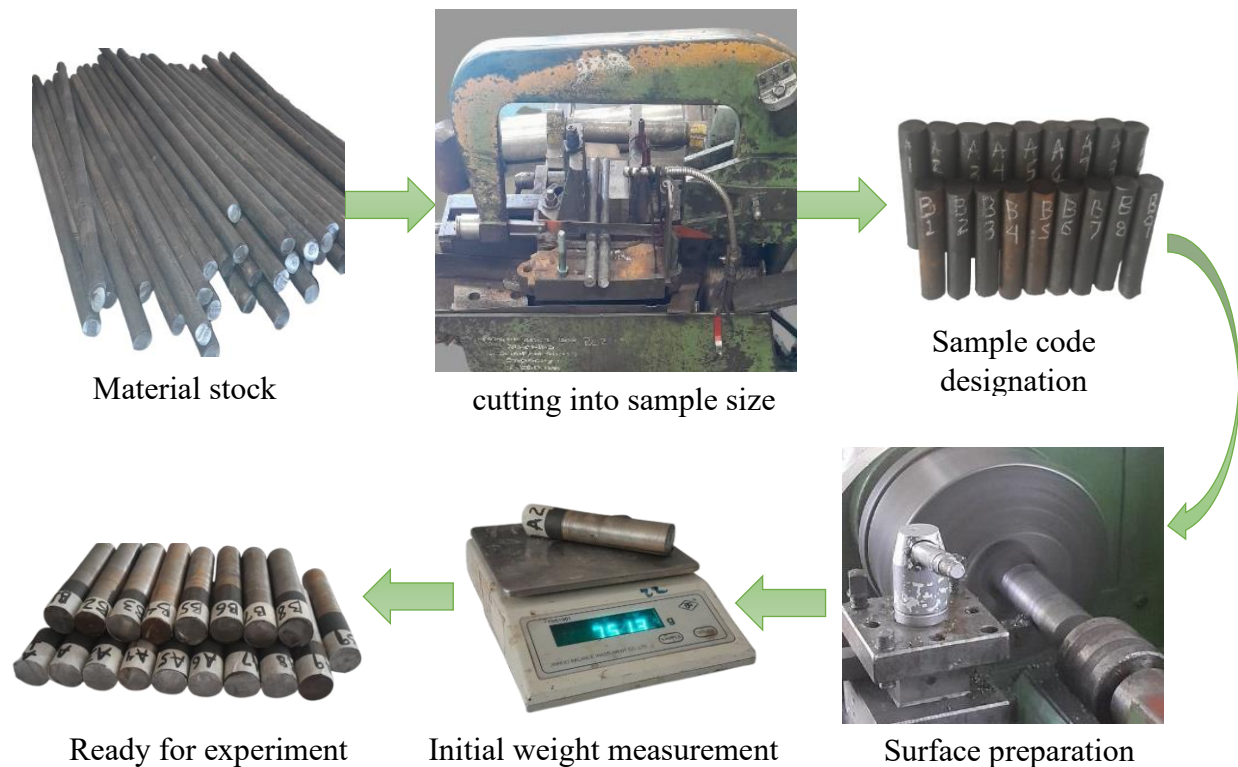


Figure 3:5 Workpiece material preparation process

3.1.6. Machine Tool

A CNC (computer numerical control) lathe machine tool is highly effective for investigating the effectiveness of such fluids while turning mild steel bars. The precision and repeatability of CNC machines allow for controlled variation of metal cutting conditions like spindle velocity, depth of cut, and feed rate. The operations ease, energy efficiency, and applicability to industries make it a

good choice for performance evaluation. Thus, the CNC lathe machine was utilized to study the performance of the prepared lubricant. The technical specification of the machine tool is presented next:

- Machine Model: EK 40
- Type: CNC Lathe
- Location: Mesfin Industrial Engineering P.L.C
- Maximum length of workpiece: 1000 mm
- Maximum Spindle Speed: 3000 RPM
- Control System: Siemens, FANUC
- Main Power supply: 3~ 380 V, 50 Hz

Cutting tool used: The tool applied for the turning operation is High Speed Steel / HSS



Figure 3:6 CNC lathe machine tool

3.1.7. Experimental Instruments and Equipment's

In this research study, several measurement systems, instruments, and nanofluid preparation equipment are employed to measure units, determine performance metrics, and prepare nanofluid. The systems help in determining key factors that influence the machining efficiency and cutting fluid performance. The measurement instruments and systems considered in this research are:

A. Surface Roughness Measuring Device

Measures the roughness of the material machined surface, which is a direct indicator of cutting performance and the effectiveness of the nano fluid in reducing surface roughness. The turned

surface was measured at two different locations, and the mean SR values were recorded using the portable type TR 100 surface tester in μm , as shown in *Figure 3:7 (a)*.

B. Digital and Analytical Balance

As shown in the *Figure 3:7 (b)* A digital balance from the geotechnical lab at Mekelle University, with higher precision, was employed to measure the initial and final weight of the workpiece accurately. The liquids used for the preparation of the proposed fluid are also measured for their weight for a proper mixing ratio. *Figure 3:8 (c)* shows the analytical balance, a highly sensitive and highly accurate instrument capable of micro-level weight measurements. This balance was utilized to accurately weigh the nano silica powder during sample preparation, ensuring precise composition ratios.



a. Surface roughness measurement; b. Digital balance; c. Infrared temperature measurement

Figure 3:7 Measuring Instruments

C. Cutting Temperature Measuring Instrument

Figure 3:7 (c) shows a digital infrared thermometer, a thermocouple, which measures the cutting temperature at the cutting region, which helps in determining the cooling and lubrication effects of the prepared fluid. The measurement was taken at a constant distance of 20cm between the workpiece and the thermometer for all samples.

D. Fluid Characterization Instruments

In this study, several key instruments were employed to ensure precise measurement and characterization of the nano-cutting fluid samples. *Figure 3:9 (a)* presents the Brookfield RV-DVE viscometer, which was applied to measure the dynamic viscosity of all the synthesized fluids, including the base fluid. This instrument allowed for controlled, repeatable viscosity measurements across different temperature settings, providing critical data for performance

comparison. This instrument can also measure ranging from 0.1 to 1000 MPa.s and 0–90 °C. As shown in *Figure 3:8* (b) illustrates that the Adwa multi-purpose digital meter [AD8000] was used for measuring both pH and temperature of the samples. This device provides reliable and consistent readings essential for evaluating fluid stability, pH, and behavior under varying conditions, and both the above instruments are found in the pharmaceutical analysis and quality assurance lab at Mekelle University.

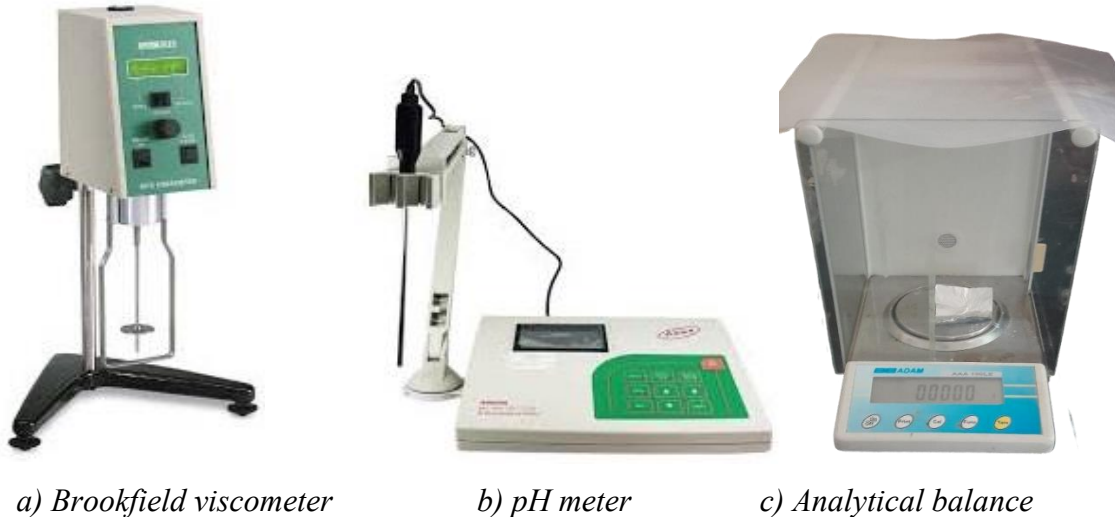


Figure 3:8 Measuring and testing instruments

E. Major Experimental Equipment's

In this experimental investigation, several necessary devices were used during the preparation phase of the nano fluid, as illustrated in *Figure 3:9* (a) shows the hot plate, which was used to heat the sunflower oil and aloe vera gel to a controlled temperature. This heating process was essential for improving fluid compatibility and enhancing the mixing efficiency. *Figure 3:9* (b) shows the MEOKO MK-001 (made in China) portable mechanical stirrer, which was employed to initiate the mixing of the base fluids (aloe vera and sunflower oil). *Figure 3:9* (c) presents the magnetic stirrer, which was used after mechanical stirring to further mix the solution and break down available particle agglomerations. Typically consists of a flat magnetic rotating base and a small elliptical magnetic stir bar placed inside the liquid container. This step was essential for the preparation of a uniform and stable nano-cutting fluid. An ultrasonic bath (Elmasonic S60H) from Addis Pharmaceuticals PLC is presented in *Figure 3:9* (d), which is used to disperse and deagglomerate particles in the solution. The device utilizes high-frequency sound waves to induce

cavitation in the fluid-filled tank, effectively breaking up precipitation and agglomerates, and ensuring uniform dispersion.



a) heat plate b) mechanical stirrer c) magnetic stirrer d) bath sonicator

Figure 3:9 Fluid preparation Equipment's

3.2. Cutting Fluid Preparation

3.2.1. Base Fluid (Aloe Vera Oil) Preparation

According to the researchers [30] [32] Aloe vera oil is prepared by combining a variety of natural oils with aloe vera extract at various proportions. Thus, in this investigation, the base fluid, which is aloe vera oil, has been prepared by mixing 30% of Aloe Vera extract into sunflower oil in a container. The Aloe vera plant is first washed, peeled, and its gel extracted. Sunflower oil is then heated, which is placed on a heat plate to a high temperature in a beaker, and the aloe vera liquid is added, allowing the mixture to boil while continuously stirred using a mechanical agitator for homogenization of the mixture. After heating for approximately 10 minutes, the mixtures are allowed to cool. Finally, the mixture or the base fluid is filtered.

3.2.2. Nanoparticle-Dispersed Cutting Fluid Preparation

There are two ways to prepare micro/ nano cutting fluid: the one-step and two-step techniques. In this experimental investigation, a two-step method is used where very small solid particles extracted as powder are mixed in a primary fluid using techniques like magnetic stirring or sonication. While it is less costly and suitable for mass production, it often leads to agglomeration. Generally, the preparation process includes the following steps:

1. **Nanoparticle Measurement:** The required amount of silica powder percentage by weight was calculated using a precise equation below [44] and weighed employing a highly accurate analytical balance as shown in *Figure 3:8* (c) in the pharmaceutical analysis and quality

control lab, Mekelle University. 0.25%, 0.5%, and 1% weight percentage of silica nanoparticles have been selected according to previous literature and the recommendations, as summarized in *Table 3.8*.

$$\phi = \frac{W_{np}}{W_{bf}} \quad \text{Eq. 3.1}$$

Where: W_{np} = mass of powder particles (nano silica)

W_{bf} = mass of the primary fluid

ϕ = weight percentage of nanoparticles in the fluid (%)

Table 3.7 Relevant articles to determine particle concentration

No.	Author	Nano particle	Base cutting fluid	Concent. wt %
1	Taha-Tijerina et al. 2019 [4]	SiO ₂	Soybean, corn, and sunflower oil	0.05, 0.10, 0.15, 0.20, and 0.25
2	Cortes et al. 2020 [16]	SiO ₂ and TiO ₂	Sunflower oil	0.25, 0.5, 0.75, 1, 1.25
3	Medhi et al. 2020 [35]	SiO ₂	Bentonite drilling fluid	0.5, 0.8, 1
4	Sankar et al. 2022 [39]	SiO ₂ , Al ₂ O ₃ and TiO ₂	SN 500 oil	0.05, 0.5, 1
5	Dambatta et al. 2024 [50]	SiO ₂	Canola, corn, and sunflower oil	0.5, 2
6	Çakır Şencan et al. 2024 [51]	SiO ₂	Sunflower oil	0.5, 1

Table 3.8 Concentration and frequency of particle dispersion

Concentration wt %	< 0.25	0.5	0.75	1.0	1.25	2
Frequency	6	5	1	5	1	2

- Mechanical Stirring:** Mechanical stirring is a crucial first step to initiate preliminary mixing of the nano powder in the primary fluid, thus improving the efficiency of the next steps. Namely, magnetic agitation and bath ultrasonication processes. The measured quantity of nanoparticles was slowly and incrementally added to the base fluid placed in a beaker. As

suggested by researchers [42], the combination was stirred at 800 rpm for 15 min with the application of a portable agitator as indicated in Figure 3:9 (b).

- 3. Magnetic Stirring:** The prepared mixtures were homogenized using a magnetic stirrer at a speed of 750 RPM for 30 minutes in the physico laboratory, Addis Pharmaceutical Factory. A magnetic stirring small bar placed inside the container ensured consistent and uniform mixing. This step was crucial to initiate the dispersion of nanoparticles within the base fluid. From the various literature, a 30-minute stirring duration was conducted based on established methodologies, while preparing the nanofluids [39], [42].

- 4. Bath Ultrasonication:** Ultrasonication plays a significant role in enhancing nanoparticle dispersion and improving the stability of nanofluids by effectively breaking down agglomerates. According to previous studies [39], [42], 30 minutes of ultrasonication is generally used to achieve dispersion. However, in this research, the fluid was initially mixed for 30 minutes, then extended to 1 hour to ensure increased stability and homogeneity [4], [44], [52], [53]. While maintaining the temperature below 55 °C, the process was conducted at a power level of 2000 W. Bath ultrasonication was carried out using ULTRASONIC BATH ELMASONIC S60H at the same laboratory for magnetic stirring.

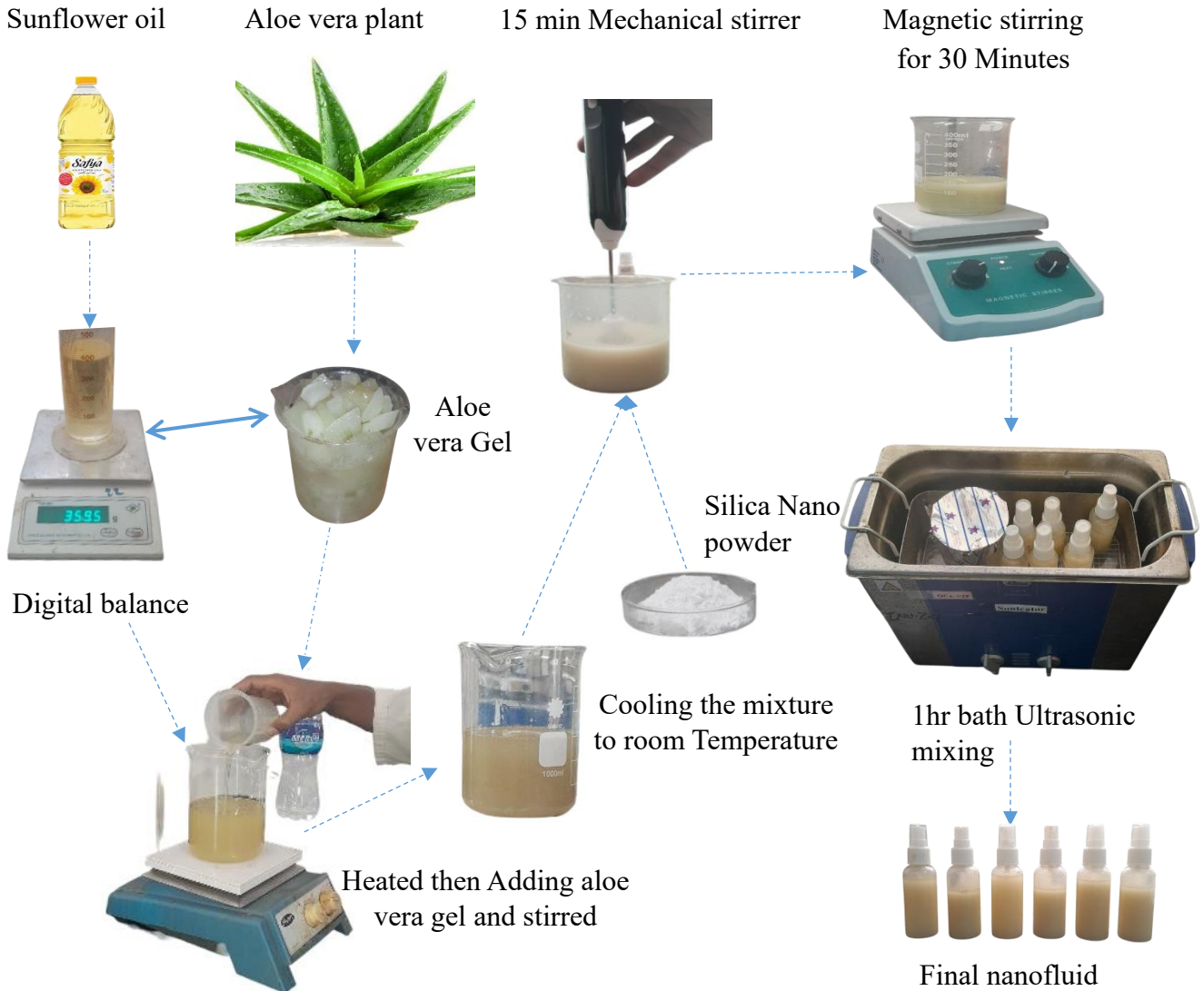


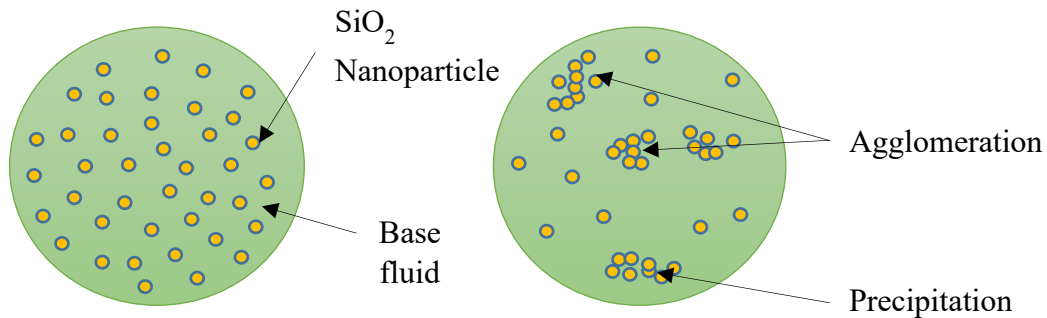
Figure 3:10 Overall graphical summary of nanofluid preparation

3.3. Characterization of the Sample Fluid

3.3.1. Sedimentation Test

Stability can be defined as how long solid particles can remain uniformly suspended in the base fluid, with minimal sedimentation or agglomeration, and without chemical reactions with the base fluid. Maintaining nanofluid stability is crucial, as it directly influences the main characteristics such as thermal conductivity and rheology, both of which are major for effective thermal flow. Particles in a fluid tend to cluster over time because of attractive forces, leading to sedimentation. Thus, increases thermal resistance, reduces heat transfer quality, and can also minimize viscosity, thereby affecting the fluid's flow property [36], [37], [44]. Nanofluid sedimentation can be

evaluated using several advanced methods. In this thesis, the formulated nano fluids were observed using a visual stability test, and their sedimentation was evaluated over a one-day time period. The figure below demonstrates possible forms of sedimentation. A homogeneous mixture of nanofluid with minimal sedimentation supports optimal performance by keeping thermal conductivity and viscosity stable.



a. Uniformly distributed nanoparticles b. Agglomerated nanoparticles in a base fluid

Figure 3:11 Dispersion of silica particles in a base fluid

3.3.2. Viscosity

Viscosity is a critical property that should be considered for assessing nanoparticle cutting fluids as it affects lubrication, cooling, and flow properties, impacting heat dissipation, friction, tool working period, and SR [10], [16], [35]. In this experimental investigation, the dynamic viscosity of the metal machining fluids was measured at Mekelle University, College of Medical Sciences, in the pharmaceutical analysis and quality assurance lab, and measured using a Brookfield Viscometer (Model: RV DVE) as shown in *Figure 3:8* (a). For consistency and to accommodate the viscosity range of the fluids, spindle number 2 was selected and operated at a speed of 100 rpm, ensuring the bubble level was centered as per the standard and procedure of the instrument. After allowing it to rotate in the oil for 2-3 min, the viscosity readings were recorded in duplicate for each sample in centipoises. Before each measurement, the viscometer was turned off, cleaned with distilled water and a soft cloth, and the spindle was turned on. To maintain the acceptable range of percentage value, the spinning speed was adjusted if it fell below 10% by increasing the speed and changing to a larger size spindle, or if it exceeded 100% by decreasing the speed and using a smaller size spindle. The measurements were performed at a controlled temperature of 25°C, 35°C, and 45°C. This procedure was applied to all the nano-enhanced cutting fluids to enable

comparative analysis. *Figure 3:12* illustrates the schematic for measuring the dynamic viscosity and pH of proposed fluids.

3.3.3. Density

Measuring the density of a nanofluid is essential, as it reflects key features like heat transfer and flow behavior, ensures accurate calculations of thermophysical parameters, monitors fluid stability, and provides essential data for simulation and system design, if available. The density of the nano-fluid is proportional to the volume fraction of powder nanoparticles and the primary fluid in the mixture. A precision balance (0.01 mg) was applied to measure the density of the synthesized fluid on a weight-to-volume basis employing a 250 mL cylindrical flask. The density of the nanofluids will be calculated with the mixing theory given by:

$$\rho_{nf} = (1 - \phi)\rho_{bf} + \phi\rho_s \quad \text{Eq. 3.2}$$

Where ρ_{nf} is the density of proposed fluid, ρ_{bf} is the density of primary fluid, ρ_s is the density of the silica powder, and ϕ is the weight proportion.

3.3.4. PH Value

The pH of a machining fluid directly influences its stability, lubrication performance, and corrosion resistance. pH variations can also affect the bioactivity of aloe vera, impacting its cooling and lubricating properties. To investigate the influence of fluid friction connected to the dynamic viscosity and rheological features of fluids, it is necessary to measure their pH level [35], [54]. Generally, the pH value provides a hint about the safety of the proposed fluid to an operator during a machining operation. Measurements are performed at room temperature (around 25°C) using a pH meter, for better accuracy, as indicated in the *Figure 3:12* (a), and the electrode is washed and dried after each use.

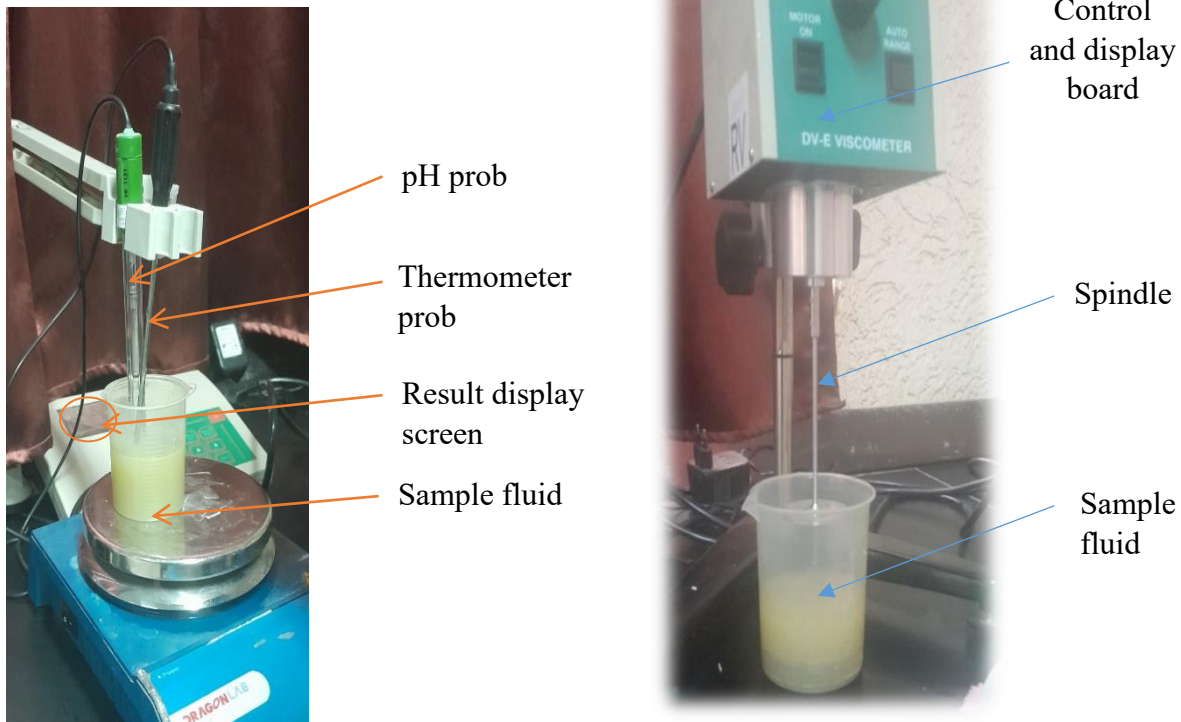


Figure 3:12 Experimental setup for a) pH meter, b) viscosity

3.4. Design of Experiment DOE

DOE is a structured approach to designing, performing, analyzing, and interpreting monitored experiments to investigate the factors affecting an operation or product. Full Factorial Design assesses possible combinations of parameters. Fractional Factorial Design also reduces the number of experiments while capturing key interactions. While Taguchi Methods uses orthogonal arrays to optimize designs with fewer trials.

The influence of a variety of parameters on the performance in this paper was evaluated by employing the orthogonal array design of experimentation first proposed by Taguchi. The Taguchi approach is a DOE method used to enhance product and process quality by optimizing performance while minimizing variability. Orthogonal arrays are employed to study multiple factors with fewer experiments, focusing on the influence of both controllable factors and uncontrollable noise factors [39], [42], [6]. For the successful implementation of the Taguchi method, the following steps are followed.

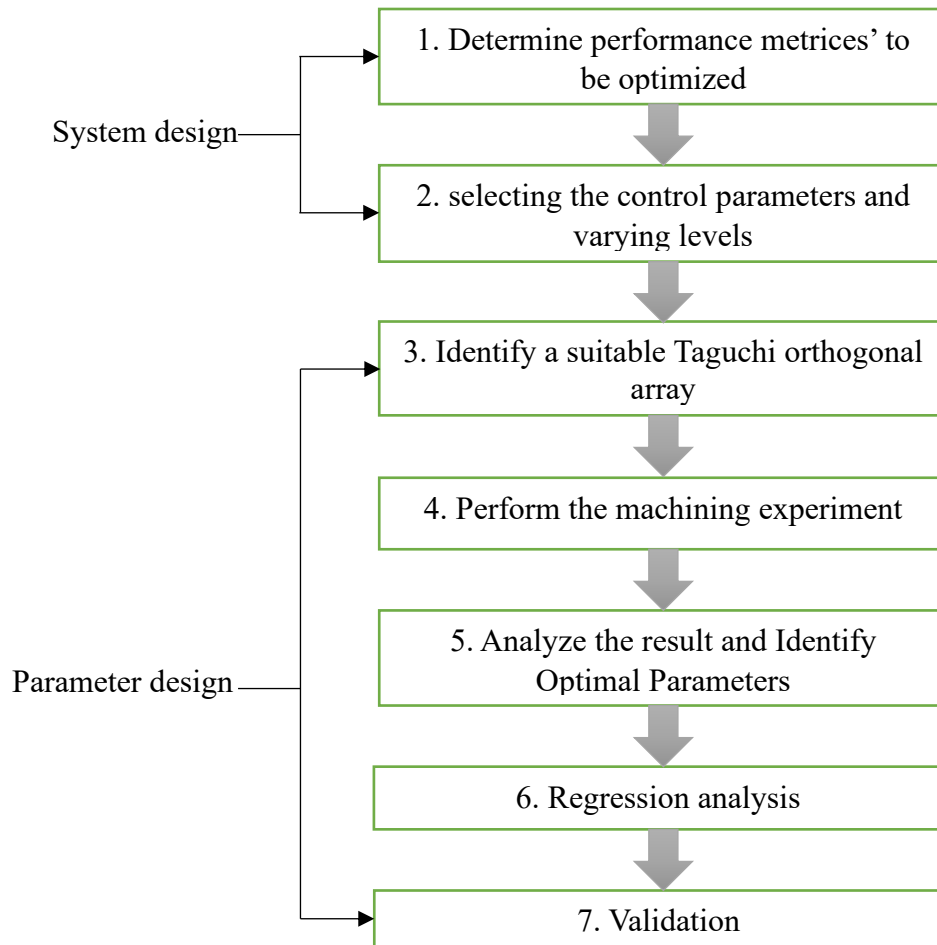


Figure 3:13 Taguchi Design Procedure adopted from literatures

3.4.1. Selection of Input Factors and Levels

Machining factors or parameters are critical variables that influence the performance and quality of machining processes. Commonly used factors include spindle speed, depth of cut, feed rate, coolant/lubricant type, and tool material. In this investigation of the effectiveness of novel nanofluid on machining performance, the identification of process conditions was in terms of previous research study, preliminary experiment, and the capacity of the machine tool. The input operation factors were varied at three levels. Accordingly, the input variables for this investigation were:

- Cutting/operation speed (m/min)
- Feed (mm/rev)
- Prepared Sample fluids at different nano silica concentrations

Table 3.9 Machining parameters selection from previous research papers

No	Author	Methods	Material	speed (m/min)	Feed (mm/rev)	Depth (mm)
1	Jaiganesh et al. 2018 [18]	Taguchi analysis, ANOVA	mild steel	56, 94, 125	0.2	1, 1.3, 1.5
2	Patwari et al. 2019 [19]	Particle Swarm Optimization	ASTM A36	22, 53, 86	0.095, 0.19, 0.38	0.5, 1, 1.5
3	Duc Trung 2021 [20]	Taguchi method, Eight MCDM	150Cr14 steel	43, 61, 86	0.08, 0.194, 0.302	0.15, 0.3, 0.45
4	S. Ghosh et al. 2022 [21]	Taguchi Method	AISI 1018	28, 46, 60	0.08, 0.16, 0.2	0.5, 1, 1.5
5	Ziyad et al. 2024 [22]	Genetic algorithm	AISI 1018	56, 76, 96	0.1, 0.14, 0.18	0.5
6	Burhanuddin et al. 2024 [5]	Taguchi-Grey Relational Analysis	ST-37 steel	23, 53, 78	0.05, 0.075, 0.1	1, 2

Table 3.10 Cutting speed selection (m/min)

Cutting speed	21-40	41-60	61-80	81-100	101-120	121-140
Frequency	2	5	3	4	0	1

Table 3.11 Feed selection (mm/rev)

Feed	0.05-0.099	0.1-0.149	0.15-0.199	0.2-0.249	0.3-0.349	0.35-0.399
Frequency	5	3	4	2	1	1

Table 3.12 Depth of cut selection (mm)

Depth	0.1 - 0.3	0.4 - 0.6	0.7 - 0.9	1 - 1.2	1.3 - 1.5	1.6 - 1.8	1.9-2.1
Frequency	2	4	0	3	2	0	1

Table 3.13 Selected machining parameters and levels

Parameter	Level 1	Level 2	Level 3
Cutting Speed (m/min)	51	71	91
Feed (mm/rev)	0.075	0.125	0.175
Particle concentration (Wt %)	0.25	0.5	1
Depth of cut (mm)	0.5	-	-

To measure the performance of fluids in turning processes, commonly measured output variables are surface roughness, tool wear, turning force, cutting zone temperature, material removal rate, chip form, and energy consumption. In this thesis work, three responses are selected.

- A. Surface Roughness (SR):** The capacity of a product to achieve its intended work effectively and for a long time depends on the tribological characteristics of that workpiece. Thermal rise while machining resulted in unwanted conditions in the surface and tool, as a result, it directly affects the quality of the product. Because of this, evaluating surface roughness is essential when determining the performance of fluid and optimizing factors for effective operation [42] [54] [55]. The measurement was repeated two times at different sides of the samples, and the average values of the measured roughness level are calculated for both experimental groups using an instrument shown in *Figure 3:7* (a) Also, the S/N ratio analysis was conducted using the "smaller-the-better" criterion.
- B. Cutting Temperature (CT):** The evaluation of CT is crucial as it directly affects tool life, surface finish, and the mechanical properties of the workpiece during turning. Observing such effects helps in selecting appropriate machining factors to minimize thermal damage and improve tool performance [42] [54] . In this study, the influence of variation in turning parameters and particle proportion on the CT was examined using a high-precision infrared thermometer, as shown in the *Figure 3:7* (c) held at a distance of 30 cm constantly.
- C. Material Removal Rate (MRR):** Determining MRR in the turning of mild steel is necessary as it reflects the efficiency and productivity of the operation. Higher MRR indicates faster operation, which in turn increases production output [20] [55]. Also, measuring MRR used for comparing the performance of different tools, cutting fluids, and machining conditions. By manipulating MRR, machinists can reduce operational costs, increase production and

minimize energy consumption. MRR was determined from measuring the weight difference of the workpieces before and after the operation [3] and applying the Eq. below.

$$MRR = \frac{W_b - W_a}{t_m * \rho}$$

Eq. 3.3

Where: **MRR** Material removal rate (mm³/sec)

W_b weight of sample material before turning, g

W_a of sample material after turning, g

t time taken to cut, sec.

ρ material density, g/cm³

3.4.2. Selection of an Orthogonal Array

The second step in the Taguchi Method, an orthogonal array of L9 (3³) is selected to optimize turning factors for maximum MRR and low SR at the lowest possible cutting temperature. The orthogonal array has nine experimental trials with three different control parameters and three experimental levels for each condition [21]. The 9 operations were performed in a random sequence created by TAGUCHI DOE in Minitab 21.2 2022 statistical software to remove any potential invisible factors. So, in this investigation, the experiments are divided into two groups:

- a. One is using the proposed nanofluid. An L9 (3³) array accommodates three factors at three levels with 9 experiments. The table below illustrates the experiment matrix:
- b. The other group is using a conventional water-soluble oil.

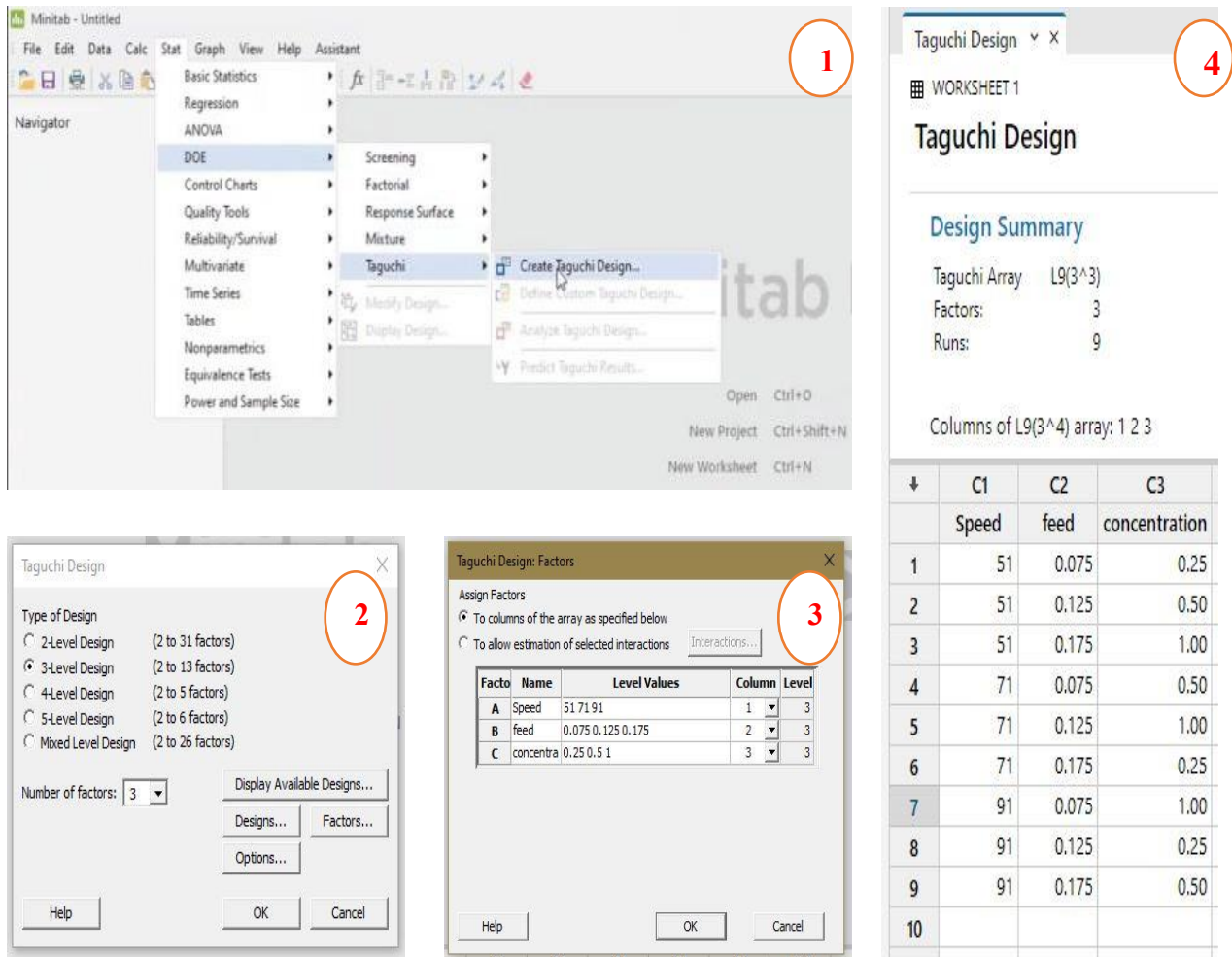


Figure 3:14 Steps in formulating TAGUCHI DOE using Minitab software

Table 3.14 Design Matrix Input Parameters for two experimental groups

		Group 1		Group 2			
Run	Speed	Feed	Concentration	CF	V (m/min)	F (mm/rev)	C (wt%)
1	L	L	L	Cf	51	0.075	0.25
2	L	M	M	Cf	51	0.125	0.5
3	L	H	H	Cf	51	0.175	1
4	M	L	M	Cf	71	0.075	0.5
5	M	M	H	Cf	71	0.125	1
6	M	H	L	Cf	71	0.175	0.25
7	H	L	H	Cf	91	0.075	1
8	H	M	L	Cf	91	0.125	0.25
9	H	H	M	Cf	91	0.175	0.5

L= Low,

M = Medium,

H = High

NF = Nanofluid,

Cf = conventional fluid

Conc.=concentration

3.4.3. Signal-to-noise (S/N) Analysis

In the Taguchi Method, the word “signal” refers to the desired value of the output characteristic, while “noise” refers to the Undesired variation represented by the standard deviation (S.D.) for the output characteristic. The signal-to-noise (S/N) ratio is the ratio of the mean to the standard deviation and is employed to determine the deviation of a quality characteristic from its desired value. The S/N ratio can be mathematically represented as:

$$S/N = -10 \log_{10} \left(\frac{\sum(Yi^2)}{n} \right) \quad \text{Eq. 3.4}$$

In Taguchi’s S/N ratio analysis, the conditions, such as larger the better, nominal the better, and smaller the better, is assumed about the desired conditions of the quality characteristic. In this thesis study, the maximum value in the material removal rate is required; the larger the better option (refer to *Eq. 3.5*) was selected. Conversely, for the SR and CT, the smaller the better criterion (refer to *Eq. 3.6*) was applied. Obtaining the minimum SR and the lowest cutting temperature is desired for the workpiece material during the turning process.

$$S/N = -10 \log_{10} \left(\frac{1}{n} \sum \frac{1}{Yi^2} \right) \quad \text{Eq. 3.5}$$

$$S/N = -10 \log_{10} \left(\frac{1}{n} \sum Yi^2 \right) \quad \text{Eq. 3.6}$$

Where: yi = measured value (MRR, surface roughness, and temperature)

n = number of replicates

3.4.4. ANOVA Analysis

When turning mild steel with an aloe vera oil-based nanofluid, ANOVA helps determine which parameters have a statistically significant impact. After experimenting with the formulated combination of parameters, using statistical software Minitab 13, ANOVA calculations are performed to obtain the F-ratio and p-value for each variable. If the p-value is less than or equal to 0.05, the factor significantly affects machining performance [5], [42], [6].

In the ANOVA, multiple quantities are involved, such as:

- (a) Degree of freedom
- (b) Sums of squares
- (c) Variance used to identify significant factors
- (d) F-ratio
- (e) Pure sum

3.4.5. Regression Analysis

RA is a statistical approach applied to investigate the relation between dependent and independent variables. It helps in predicting results, identifying trends, and understanding how variation in one or more independent variables changes a dependent variable. Also, interaction effects are analyzed by including interaction terms, which are the product of two independent variables. If the interaction term is statistically significant, it indicates that the effect of a single variable depends on the level of another. For a simple linear regression, the mathematical equation employed to create the linear equation is shown in Eq.3.7.

$$Y = \beta_0 + \beta_1 X + \varepsilon \quad \text{Eq. 3.7}$$

Where: β_0 is the intercept,

β_1 is the slope (coefficient of X),

ε is the error term.

3.5. Multi-Response Optimization

3.5.1. Grey Relational Analysis

Taguchi-Grey Relational Analysis (GRA) is applied for multi-response optimization and decision making in cutting operations. It combines Taguchi's robust design method with GRA to find the optimal combination of process parameters from the formulated combinations, when multiple outputs need to be optimized simultaneously. This analysis is done in Microsoft Excel 2024. In this stage, four steps are involved [5], [39], [44].

I. Normalize the Experimental Data: Convert response values into a dimensionless scale using min-max normalization.

Lower-the-better (surface roughness and cutting temperature)

$$Xi = \frac{\max(Y) - Yi}{\max(Y) - \min(Y)}$$

Eq. 3.8

Higher-the-better (material removal rate)

$$X_i = \frac{Y_i - \min(Y)}{\max(Y) - \min(Y)}$$

Eq. 3.9

X_i → Normalized (dimensionless) value of the i^{th} experiment

Y_i → Actual experimental value of the response

$\max(Y)$ → Maximum value among all observed response values

$\min(Y)$ → Minimum value among all observed response values

II. Calculate Grey Relational Coefficients: Compute GRC to measure the closeness of each response to the ideal value using the equation.

$$\xi_i = \frac{\Delta_{min} + \zeta \Delta_{max}}{\Delta_i + \zeta \Delta_{max}}$$

Eq. 3.10

ξ_i = grey relational coefficients

Δ_i = difference between ideal and actual response (1-actual), deviation

Δ_{min} → Minimum value among all Δ_i values

Δ_{max} → Maximum value among all Δ_i values

ζ = distinguishing coefficient (usually 0.5)

III. Compute Grey Relational Grade: is determined by calculating the average value of the Grey Relational Coefficients for all responses. Higher GRG demonstrates a favorable overall performance.

$$GRG_i = \frac{1}{n} \sum \xi_i$$

Eq. 3.11

IV. Identify Optimal Parameter Combination: The highest GRG value corresponds to the best machining parameter combination. Compute the average grade from the GRG result to select optimal parameters for every level.

3.5.2. TOPSIS

One of the effective multi-response optimization approaches is TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), which is commonly applied in the process of data analysis to handle the problems related to multiple objectives. It finds the optimal input parameters by ordering alternatives according to their proximity to the ideal outcome [20]. The analysis was performed in Microsoft Excel 2024. Steps followed during the calculation of the TOPSIS Method are:

Step 1: Normalize the Decision Matrix: Convert raw data X_{ij} into normalized values r_{ij} , ensuring comparability. n , total number of alternatives. This removes units and scales all data to a comparable range.

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^n X_{ij}^2}}$$

Eq. 3.12

Step 2: Construct the Weighted Normalized Matrix

Assign weights in terms of their importance, subjectively using a manual or objectively using the entropy weighing method. Multiply each column by its associated weight to get the weighted normalized matrix.

$$v_{ij} = w_{ij} * r_{ij}$$

Eq. 3.13

v_{ij} → Weighted normalized value of the i^{th} alternative with respect to the j^{th} criterion

w_j → Weight assigned to the j^{th} criterion (reflecting its importance)

Step 3: Identify the Ideal (Best) and Negative-Ideal (Worst) Solutions

Ideal Solution (best): $v^+ = \{\max v_{ij} \text{ (for benefit), } \min v_{ij} \text{ (for cost)}\}$

Negative Ideal (worst): $v^- = \{\min v_{ij} \text{ (for benefit), } \max v_{ij} \text{ (for cost)}\}$

Step 4: Calculate Separation Measures: Using Euclidean distance

Distance to ideal:

$$s^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2}$$

Eq. 3.14

Distance to negative ideal:

$$s^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2}$$

Eq. 3.15

$S_i^{+/-}$ → Separation distance of the i^{th} alternative to the ideal (best) and negative ideal solution

v_{ij} → Weighted normalized value of the i^{th} alternative under the j^{th} criterion

$v_j^{+/-}$ → Ideal (best) and negative ideal (worst) value for the j^{th} criterion

n → Total number of criteria

Step 5: Compute Closeness Coefficient

$$CC_i = \frac{s_i^-}{s_i^+ + s_i^-}$$

Eq. 3.16

The closer CC_i is to 1, the better the alternative.

Step 6: Rank the Alternatives

Rank all the experiments based on their CC_i values. The highest CC_i indicates the best overall compromise solution among the responses.

Entropy Weighting Method

This Method is an objective way to find the weight (importance) of every criterion in a decision matrix by measuring the variability of information. Steps involved are:

Step 1: Normalize the Decision Matrix: Convert raw data x_{ij} into normalized values r_{ij} , ensuring comparability.

$$r_{ij} = \frac{x_{ij} - x_j^{min}}{x_j^{max} - x_j^{min}}$$

Eq. 3.17

Step 2: Construct the Proportion Matrix: Divide each normalized value by the sum of its column. Where m is total number of experiments.

$$P_{ij} = \frac{r_{ij}}{\sum_{i=1}^m r_{ij}}$$

Eq. 3.18

Step 3: Calculate Entropy for Each Criterion

$$E_j = -K \sum_{i=1}^m P_{ij} \ln(P_{ij}) \text{ ,, where Constant, } K = \frac{1}{\ln(m)}$$

If $P_{ij} = 0$, treat $P_{ij} \ln(P_{ij}) = 0$

Eq. 3.19

Step 4: Calculate the Degree of Diversification

$$D_j = 1 - E_j$$

Eq. 3.20

Step 5: Determine Final Weights

$$w_j = \frac{d_j}{\sum_{j=1}^n d_j}$$

Eq. 3.21

3.6. Experimentation Setup

The workpiece was securely mounted in the headstock, and its alignment was checked. The CNC program with selected conditions: feed, spindle velocity, calculated as *Eq. 3.22*, at the same Depth of cut of 0.5 mm, was programmed by the machine operator and loaded with a flash disc into the machine control unit. The CNC Turning for a sample length of 80mm was performed, and the time taken was also recorded using a stopwatch. The weight of the workpiece material was determined before and after the turning operation in the precision weight balance in the civil engineering laboratory EIT-M.

The setup for supplying the nanofluid lubricant to the machining zone is as previously used by researchers [56]. It was designed to ensure a consistent and controlled flow. The lubricant, containing solid suspensions, was stored in a small fluid container positioned above the machining axis, allowing the fluid to flow under the influence of gravity and atmospheric pressure. A

regulating valve was installed to control the lubricant flow speed, which was checked by collecting and quantifying the amount of lubricant at different valve positions over a specific period. A flow rate of 10 ml/min was sufficient for effective lubrication [38] [56].

Once this flow rate was established, it was maintained consistently throughout the two groups of experiments. The lubricant was precisely dispensed through a 0.5 mm outer diameter tip, ensuring direct application onto the top surface of the HSS tool. Therefore, in this study, a medical IV drip tube was utilized to allow the fluid flow to be controllable and measurable, as indicated in the *Figure 3:15*. After verifying the steady flow of lubricant, machining operations were performed under controlled conditions to assess the performance of the nanofluid in improving machining efficiency [31], [55], [34], [56], [57].

$$spindle\ speed = N = \frac{1000 * V}{\pi * D}$$

Eq. 3.22

Which; N = spindle speed, rpm

V = cutting speed, m/min

D = diameter of workpiece, mm

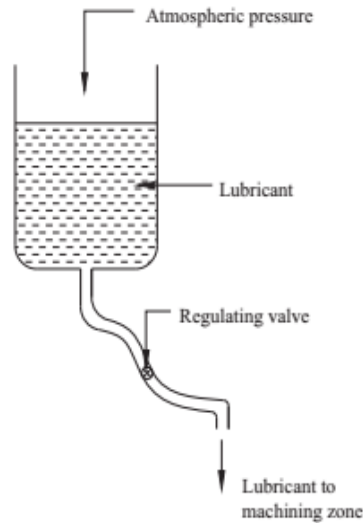


Figure 3:15 Minimum quantity lubrication Methode used [56]

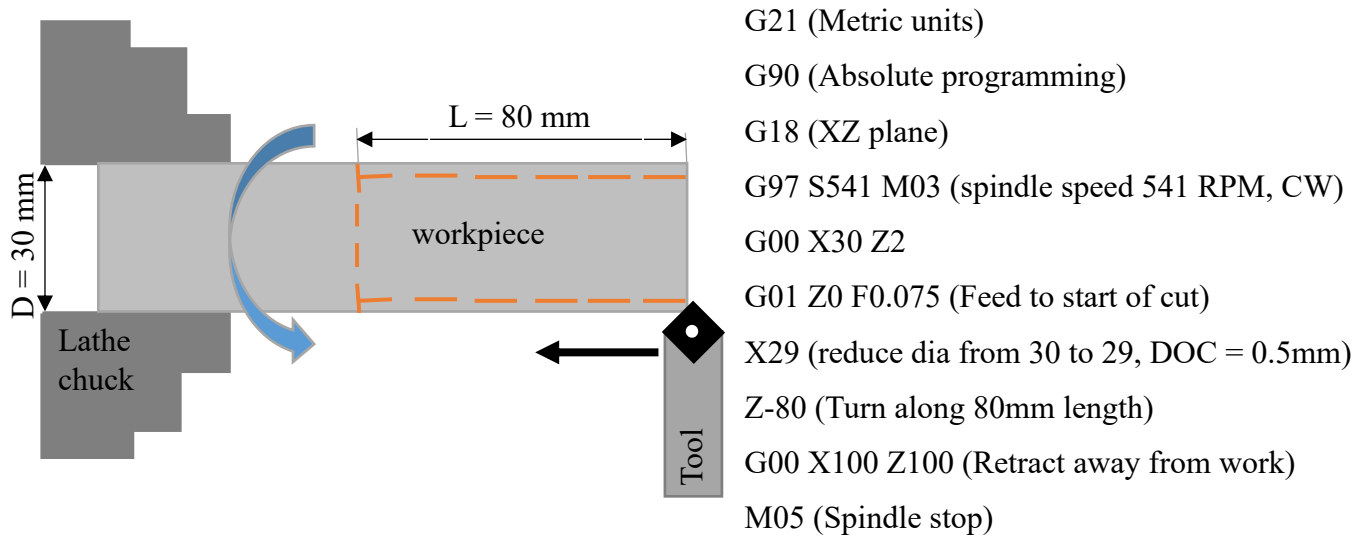


Figure 3:16 Schematic of the machining turning operation with CNC code to the first run

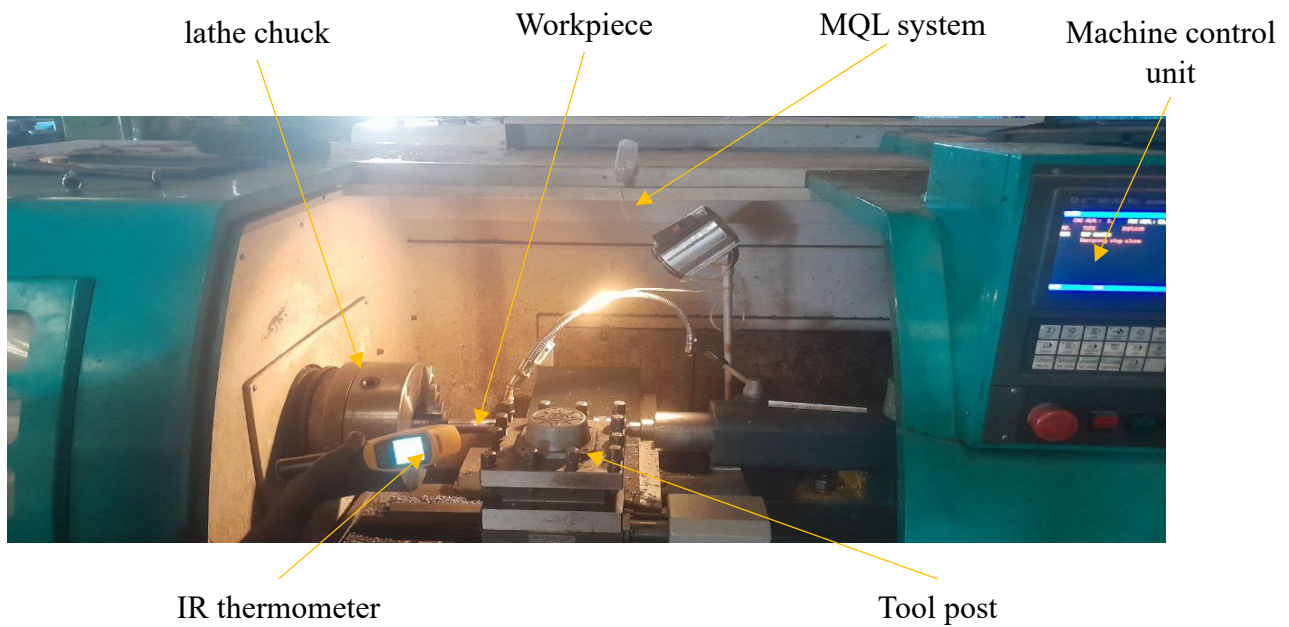


Figure 3:17 machining experimentation setup and product

Chapter Four

4. Results and Discussion

4.1. Thermo-Physical Properties of the Cutting Fluid

Nanofluid characteristics depend mainly on factors like Thermophysical, lubrication, particle matter, heat transfer, particle size, concentration, and colloid. This chapter presents and analyzes the experimental results of basic characteristics of the prepared cutting nanofluid, including density, viscosity, pH, and stability. These properties are essential for understanding the behavior and performance of the nanofluid during machining. The results are discussed according to their fluid composition and nanoparticle concentration to check their suitability for sustainable and effective machining processes.

Table 4.1 shows the overall results of the thermophysical properties of the prepared fluids

Fluid type	Density (g/cm ³)	Viscosity @35 °C	Ph	Relative Stability
Sunflower oil	0.899	42.8	-----	-----
Base fluid	0.915	30.7	6.2	-----
Sample fluid 1	0.918	41	6.2	Good
Sample fluid 2	0.921	46.3	6.3	Better
Sample fluid 3	0.928	52.2	6	Low

4.1.1. Sedimentation Result and Discussion

Figure 4:1 shows the prepared base fluid after heat-stirring. Initially, a gel-like mixture appears due to the applied temperature during stirring, which helps partially mix the aloe vera with the sunflower oil. However, because of the density difference, the aloe vera settles to the bottom slowly over time, resulting in observable phase separation into two different regions.

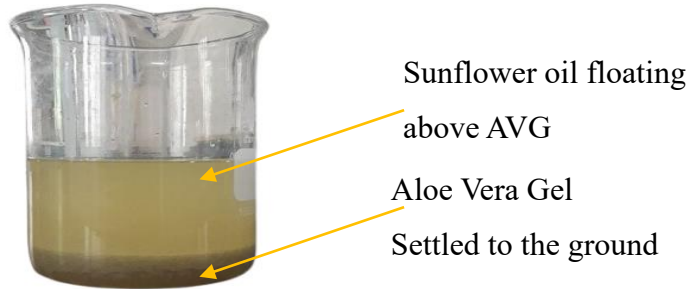


Figure 4:1 Stability visual observation of the base fluid after an hour



Figure 4:2 The prepared fluids at different silica concentrations

Figure 4:2 Shows the synthesized nanofluid with different nano silica concentrations. At the beginning, the fluid appears white and homogeneous when observed with naked eye due to effective mixing during preparation. However, after 24 hours of shelf sedimentation testing, phase separation was observed, creating different regions as the constituents gradually settled according to their density level.



Figure 4:3 Stability observation of the three sample nanofluids after one day

The prepared nano-cutting fluid samples display three separated phases based on the density behavior of the primary components:

- Due to its relatively lower density, sunflower oil is predominantly present in the first region, which is region A.
- Region B is the intermediate phase where aloe vera gel is formed and remains suspended between the oil and the denser solid particles. This layer appears just below the sunflower oil and above the settled nano silica, indicating a stable emulsion or dispersion interface.
- Region C, which is located at the bottom of the container, contains mainly silica powder. Because of its higher density, the silica particles settle by gravity, forming a sedimented third layer.

All three fluid samples are consistent with this three-phase arrangement, provided that the relative volume proportions of each component are maintained. However, raising the concentration of silica powder resulted in a proportional rise in the size of sedimented material within Region C, thus changing the thickness or compactness of that phase. Accordingly, the key factor that should be aware of during nanofluid synthesis is, how the components interact with each other, considering various mixing and homogenization mechanisms like increasing the time during heating, agitating ultrasonication, and addition of surfactants such as SDS (sodium dodecyl sulphate), oleic acid, lecithin and many more as suggested by other researchers, should be used to achieve long last sedimentation result and homogenized mixture.

4.1.2. Viscosity Result and Discussion

Figure 4:4 below presents the viscosity of sunflower oil, base fluid, and nanofluid at three variations of temperatures (25 °C, 35 °C and 45 °C), indicating their property under thermal variation rising during machining. As the proportion of particles rises (0, 0.25, 0.5, and 1%), the dynamic viscosity of the fluid increases linearly. Among the samples, viscosity increases with higher concentrations of nano silica, which is 1 wt% of SiO₂, exhibiting the highest values at each temperature, specifically at the lowest temperature. This indicates that nanoparticles contribute to fluid thickening, which enables them to exhibit resistance to flow behavior. Therefore, it will have better film formation between the material and the tool, which improves lubrication and reduces workpiece-tool friction, thus minimizing temperature generation, which in turn helps to minimize tool wear and roughness. Notably, at 25 °C, viscosity ranges from 54.4 to 69.3 mPa.s, while at 45

°C, as is expected, it is reduced below 34.6 mPa.s for all samples, confirming the thermal sensitivity of the proposed fluids.

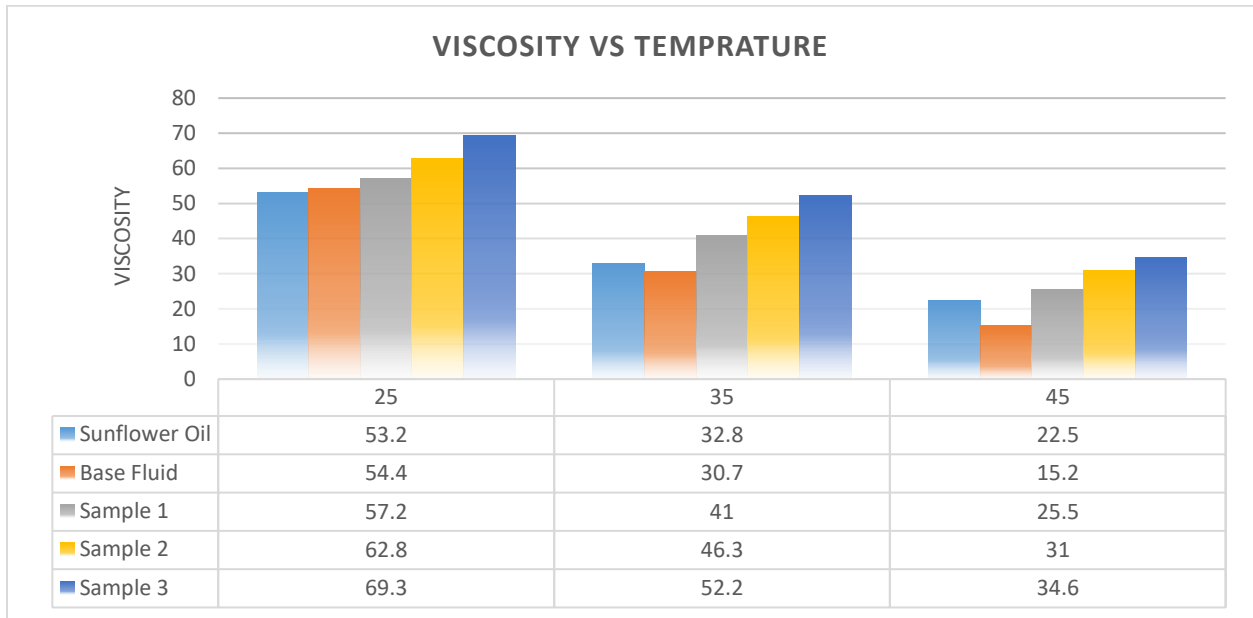


Figure 4:4 Viscosity to temperature bar chart for all five fluids

4.1.3. Density and pH Value Result and Discussion

From *Table 4.1* The calculated density using *Eq. 3.2* The pH measured values of the prepared cutting fluid are shown. It is observed that as the proportion of nano silica in the fluid increases, the density slightly increases, attributed to the inherently higher density of silica particles relative to the base fluid's primary components. Additionally, the pH values of the samples were observed to range from 6 to 6.2. The base fluid (sunflower oil and aloe vera) exhibited a slightly higher pH of around 6.2, influenced by the aloe vera liquid behavior. However, as the silica concentration increased, the pH values slightly varied for each sample. This result suggests that the addition of nano silica powder doesn't contribute much to variation in pH of the fluid, making it more suitable for healthy machining operations.

4.2. Result Analysis and Discussion of Surface Roughness

4.2.1. Signal-to-Noise (S/N) Analysis of Surface Roughness

As indicated in *Table 4.2*, surface roughness has been measured at two different surfaces for each experimental material sample, and the mean values were taken to reduce the measurement fault for both the experimental group means for the nanofluid and conventional fluid. Additionally, the

signal-to-noise ratio was computed. Accordingly, in almost all experiments, the nanofluid consistently produced lower average surface roughness values than the commercial fluid, as indicated in *Figure 4:5*. A maximum of 22.84% improvement was observed in Experiment 7, likely due to effective lubrication at higher nanoparticle concentration. Generally, compared with the utilization of conventional fluid, an average of 10.28% performance increment has been observed.

Table 4.2 Results and S/N Ratios for Surface Roughness

Exp. No	Nanofluid				Conventional fluid				Impro.
	R 1	R 2	Average	S/N	R 1	R 2	Average	S/N	
1	1.92	1.68	1.8	-5.10545	1.9	1.84	1.87	-5.4368	3.74%
2	2.66	3.04	2.85	-9.0969	3.08	2.96	3.02	-9.6001	5.63%
3	3.82	3.48	3.65	-11.2459	4.1	4.7	4.4	-12.8691	17.05%
4	1.72	1.88	1.8	-5.10545	1.92	1.86	1.89	-5.5292	4.76%
5	1.63	1.87	1.75	-4.86076	2.3	2.1	2.20	-6.8485	20.45%
6	3.78	4.12	3.95	-11.9319	4.25	4.37	4.31	-12.6895	8.35%
7	1.16	1.34	1.25	-1.9382	1.5	1.74	1.62	-4.1903	22.84%
8	2.04	1.86	1.95	-5.80069	2.05	2.01	2.03	-6.1499	3.94%
9	2.95	2.65	2.8	-8.94316	3.02	2.92	2.97	-9.4551	5.72%

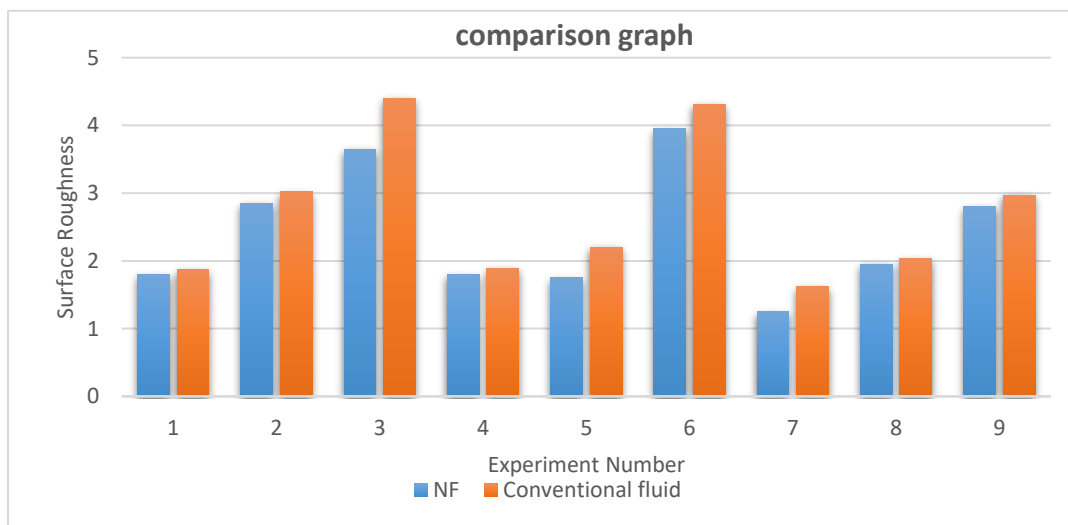


Figure 4:5 Comparison chart of SR between NF and Conventional fluid

Figure 4:6 below shows the main effects of turning spindle speed, feed rate, and nanoparticle concentration on average SR using the synthesized nanofluid. Higher speeds reduced SR due to reduced built-up edge and thermal softening of the material. Surface roughness increased with feed, consistent with established machining theory. A Higher concentration (1%) at experiment number 7, followed by 5, resulted in the best surface finish, likely due to improved thermal and rheological features of the fluid. This confirms that the nanofluid, specifically at the higher concentration, by reducing friction and heat in the machining zone, significantly enhances surface quality.



Figure 4:6 Main effect diagram of factors on SR

4.2.2. Analysis of Variance (ANOVA) for Surface Roughness

From the ANOVA result *Table 4.3* Feed rate is the only statistically significant parameter ($P = 0.043 < 0.05$). It had the highest contribution of 75.91%, indicating that variation in feed rate emerged as the most dominant factor affecting surface finish. The observation aligns with theoretical machining principles, which show that increased feed tends to increase surface roughness due to wider feed marks and increased cutting intensity or engagement.

The result shows cutting speed had a moderate influence with a contribution of 14.53%, although it was not statistically significant ($P = 0.192 > 0.05$). However, with more replicates or better variance control, its F-value (4.22) suggests it may become significant.

Silica concentration, which is the third parameter, had a minimal effect on surface roughness in this study, which contributes only 6.11%, and was statistically non-significant ($P = 0.360$). This may suggest that within the tested concentration range, the rheological and thermal benefits of nanoparticles reached a saturation point or were covered by the other mechanical parameters.

The model's R^2 value of 92.98% ensures the model's strong agreement with the experimental results, meaning that most of the deviation in S/N ratios is defined by the chosen parameters. Even so, the adjusted R^2 of 71.93% suggests some overfitting or that the number of factors relative to degrees of freedom was slightly high, calling for further validation with a larger sample size.

Table 4.3 ANOVA for SN Ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution
Cutting Speed (m/min)	2	12.962	12.962	6.481	4.22	0.192	14.53%
Feed (mm/min)	2	67.734	67.734	33.867	22.05	0.043	75.91%
Silica Conc. (wt%)	2	5.454	5.454	2.727	1.78	0.360	6.11%
Residual Error	2	3.072	3.072	1.536			
Total	8	89.222					

Model Summary: $S = 0.4953$, $R-Sq = 92.98\%$, $R-Sq(adj) = 71.93\%$

From the ANOVA results, it is evident that feed is the most critical factor in minimizing SR when using the developed nanofluid. Although cutting speed and nanoparticle concentration were found to be statistically insignificant at the 95% confidence interval, they still contribute meaningfully to surface finish and should be optimized for best results.

4.2.3. Selection of Optimal Levels and Regression Model for Surface Roughness

According to the S/N ratio and ANOVA results, the most favorable levels of process conditions were identified. Also, a linear regression model was generated to predict SR as a function of input factors, with validation based on R^2 and residual analysis.

Table 4.4 Response for Signal-to-Noise Ratios

Smaller is better

Level	Cutting Speed (m/min)	Feed (mm/min)	Silica Conc. (wt%)
1	-8.483	-4.050	-7.613
2	-7.299	-6.586	-7.715
3	-5.561	-10.707	-6.015
Delta	2.922	6.657	1.700
Rank	2	1	3

As clearly shown in the above table and *Figure 4:7* The optimal levels for yielding the lowest SR as determined from the response for S/N ratios are:

- Cutting Speed: Level 3 (91 m/min)
- Feed: Level 1 (0.075 mm/rev)
- Silica Concentration: Level 3 (1 wt%)

Lower feed and higher cutting speed produce smoother surfaces, and higher particle concentration in the fluid can enhance lubricity and cooling effects, ensures the selections are aligned with the general machining concept. Also, the linear Regression equation obtained is:

$$Ra (\mu m) = 1.748 - 0.01917 \text{ Cutting Speed} + 18.50 \text{ Feed} - 0.476 \text{ Silica Conc.}$$

Model Summary, $S = 0.394139$, $R-sq = 88.89\%$, $R-sq(adj) = 82.22\%$, $R-sq(pred) = 60.34\%$

The lower $R-sq(pred)$ value of 60.34% suggest that a linear model may not fully capture the complex interactions between parameters. For improved accuracy of prediction, A quadratic regression model including interaction terms (e.g., speed \times speed, feed \times speed, feed \times concentration) should be developed. Further experimental validation is recommended to refine and validate the regression model across wider ranges or finer intervals of level of parameters.

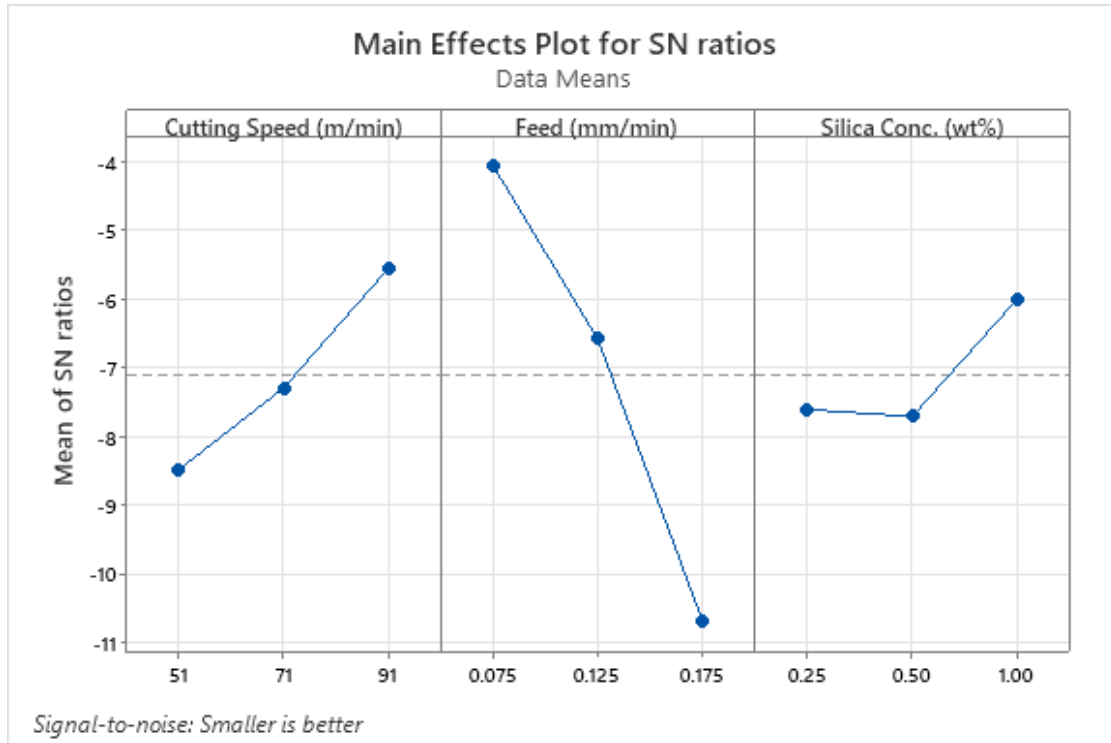


Figure 4:7 Main effect graph for SN ratios

4.3. Result Analysis and Discussion of Material Removal Rate

4.3.1. Signal-To-Noise (S/N) and Effect of Input Parameters on MRR

The table shown below is the MRR result, which is calculated by using the *Eq. 3.3* And the S/N ratio was subsequently computed using Minitab software based on the higher the better criteria. In this analysis, a greater S/N ratio value reflects superior machining efficiency with reduced variability due to uncontrolled conditions such as tool abrasion, chip adhesion, or workpiece vibration. The experimental results comparing nano cutting fluid (NF) and conventional fluid demonstrate consistently higher MRR and S/N ratios for the nano fluid.

Table 4.5 Results and S/N Ratios for MRR

Run No.	Nano fluid					Conventional fluid					Imp.
	W _i	W _f	M _t	MRR	S/N	W _i	W _f	M _t	MRR	S/N	
1	744.1	707	126	37.419	31.4618	738.9	701	123	39.2	30.6513	-4.8
2	751.2	711	87	58.125	35.2873	742.7	705.3	92	51.7862	34.5251	10.9
3	733.7	689	61	93.862	39.4498	737.2	699	57	85.3727	38.6264	9

4	745.5	701	105	54.125	34.6680	746	705.3	94	55.1565	34.8319	-1.83
5	737.2	690.5	60	99.305	39.9394	736.9	688	72	89.8797	39.0732	10.48
6	770.5	729	51	103.54	40.3022	741.3	705	47	98.3873	39.8588	5.24
7	746.9	688.7	90	85.330	38.6220	738.5	691	78	77.5764	37.7946	9.97
8	775.2	733	57	94.31	39.5353	741.8	711	45	87.1904	38.8094	8.16
9	731.5	693.5	35	137.70	42.7787	740.2	705.4	38	116.661	41.3385	18.01

W_i = Initial weight, g

W_f = final weight, g

M_t = machining time, s

MRR = material removal rate, mm^3/s

From the result and the indicated comparison graph *Figure 4:8* It is evident that the proposed fluid increases MRR consistently across all trails except for the experimental trials 1 and 4, at which silica concentration within the fluid is at a low level. Overall enhancement in MRR using nanofluid compared to the conventional one is to be averaged 7.23%. This is because of the modified cooling and lubrication property of the fluid by the silica powder, aloe vera, and sunflowers' synergistic effect, which helps reduce cutting resistance and improve chip evacuation, especially in the experimental trial having a high silica concentration level.

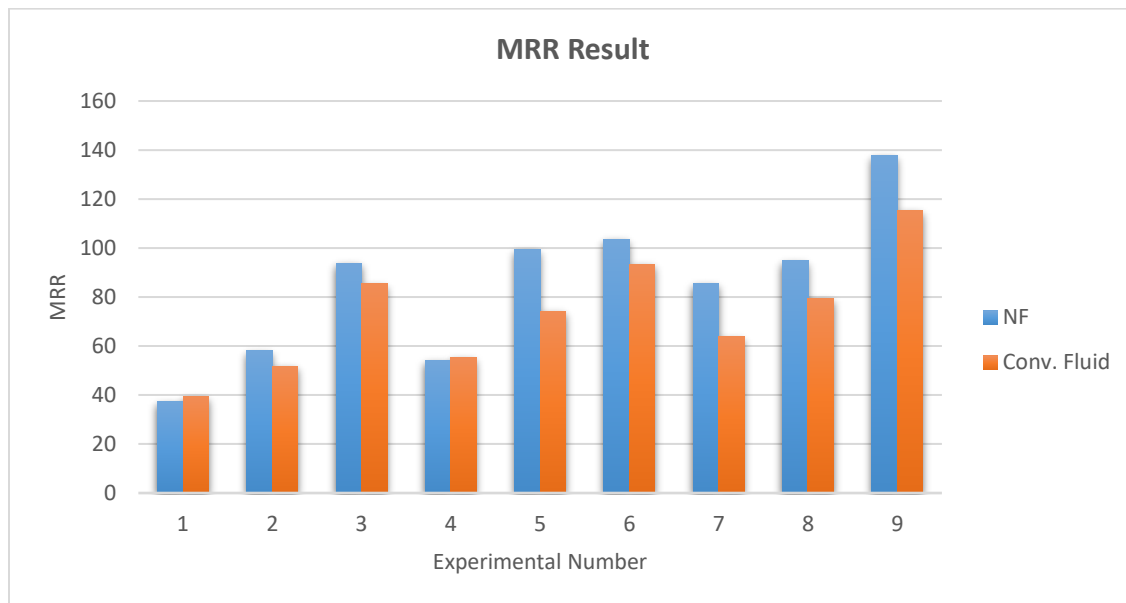


Figure 4:8 Comparison chart of material removal rate between NF and Conventional fluid

The plot *Figure 4:9* indicates that feed rate and spindle speed have the highest significant positive contribution to MRR, with both showing upward trends. Particle concentration also increases performance, but with a minor effect. This shows that increasing spindle speed and feed increases machining productivity (MRR).

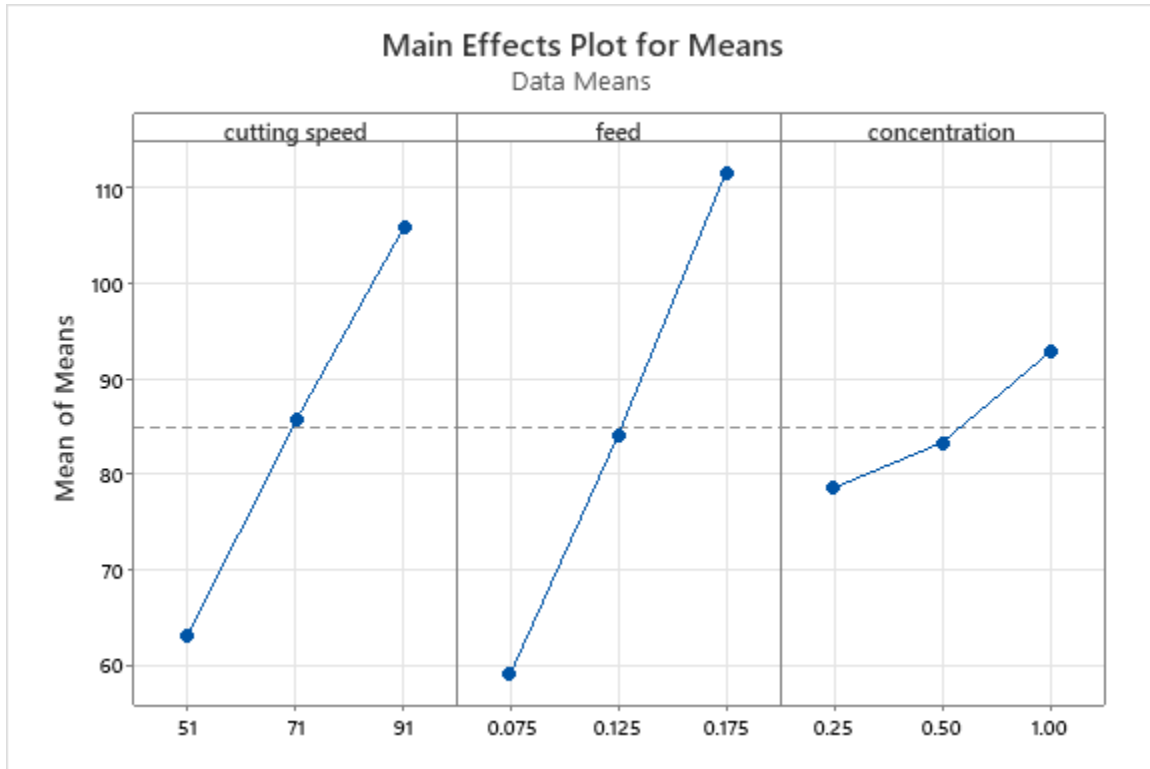


Figure 4:9 Main effects graph for input parameters on MRR

4.3.2. Analysis of Variance (ANOVA) for Material Removal Rate

Table 4.6 shows the outputs of the analysis of variance (ANOVA) for the effect of feed rate, cutting speed, and nanoparticle concentration on the MRR. The evaluation shows how each parameter contributes to the variation in MRR and whether its effects are statistically significant.

Accordingly, Of all parameters, feed has the highest impact on MRR, contributing of 54.06% to the total variation. It also has the greatest F-value of 807.14 and a very low p-value of 0.001, indicating a statistically significant parameter. Cutting speed in turn significantly influences MRR, having a contribution of 37.36% of the variation, with an F-value of 557.76 and p-value of 0.002. nanoparticle concentration has a smaller but statistically significant contribution of 8.5%, supported by its F-value of 126.94 and p-value 0.008. The minimal residual error of 0.0328 indicates that the model shows a good fit with little unexplained variation.

All three input variables, cutting speed, feed rate, and nanoparticle concentration, have a statistically significant effect on material removal rate (MRR). Among these factors, feed rate has the strongest influence, with cutting speed and concentration having secondary and tertiary effects, respectively.

Table 4.6 Analysis of Variance for SN Ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution
cutting speed	2	36.5971	36.5971	18.2986	557.76	0.002	37.36 %
Feed	2	52.9601	52.9601	26.4800	807.14	0.001	54.06 %
concentration	2	8.3288	8.3288	4.1644	126.94	0.008	8.5 %
Residual Error	2	0.0656	0.0656	0.0328			
Total	8	97.9517					

Model Summary, $S = 1.2152$, $R\text{-Sq} = 96.81\%$, $R\text{-Sq}(\text{adj}) = 87.23\%$

$$\text{Contribution percentage} = \frac{\text{Seq SS}}{\text{total Seq SS}} * 100\%$$

4.3.3. Regression Equation and Selection of Optimal Levels For MRR

A regression equation is developed to model the relationship between MRR and the input variables. Accordingly, a linear regression model was developed to predict MRR as a function of input variables.

Regression Equation:

$$\text{MRR} = -68.1 + 1.070 \text{ cutting speed} + 527.4 \text{ feed} + 19.00 \text{ concentration}$$

Model Summary: $S = 6.36416$, $R\text{-sq} = 97.28\%$, $R\text{-sq}(\text{adj}) = 95.64\%$, $R\text{-sq}(\text{pred}) = 89.67\%$

The above model summary values indicate that the equation explains a very high proportion of variability in MRR and generalizes well to new data. The model can be reliably utilized to optimize the process and input in the turning operations employing nanofluids.

Table 4.7 Response Table for Signal-to-Noise Ratios

Larger is better

Level	Cutting speed	feed	concentration
1	35.40	34.92	37.10

2	38.30	38.25	37.58
3	40.31	40.84	39.34
Delta	4.91	5.93	2.24
Rank	2	1	3

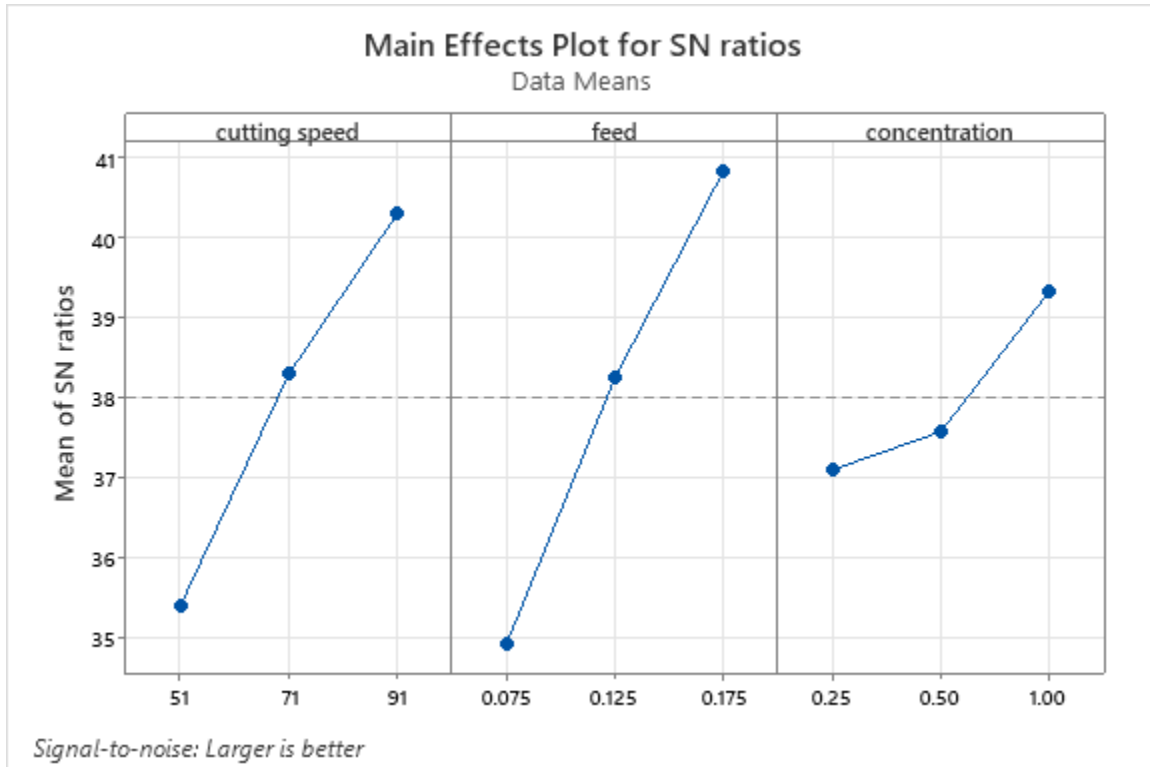


Figure 4:10 Main effect diagram for S/N ratios of input parameters on MRR

From the *Table 4.7* and *Figure 4:10* Feed rate has the highest positive impact on MRR, followed by cutting speed, and then particle concentration. Also, the optimal levels for maximum MRR are:

- Cutting Speed: Level 3 (highest speed)
- Feed Rate: Level 3 (highest feed)
- Silica Concentration: Level 3 (highest concentration)

These selected combinations align with theoretical expectations, as higher spindle speed and feed, will result in maximized chip volume per unit time, while higher silica content increases thermal conductivity and lubricity, reducing workpiece-tool friction.

4.4. Result Analysis and Discussion of Cutting Temperature

4.4.1. Signal-To-Noise (S/N) and Effect of Input Parameters on Temperature

In this investigation, the performance of nanofluid and conventional cutting fluids is compared based on cutting temperature using the smaller-the-better criterion in S/N ratio analysis, as lower cutting temperatures are desirable to increase machining performance and the lifespan of the tool.

Table 4.8 The measured CT value for both experimental groups. Also presents the S/N analysis computed applying the "smaller-the-better" criterion for cutting temperature. It shows how each parameter influences heat formation during the turning process.

Table 4.8 Experimental Results and S/N Ratios for Cutting Temperature

Run Number	Using nanofluid	S/N	Conventional fluid	S/N	Improvement
1	37.0	-31.3640	37.8	-31.5498	2.12%
2	36.7	-31.2933	38.6	-31.73174	4.94%
3	36.9	-31.3405	40.4	-32.12762	8.66%
4	37.9	-31.5728	41.4	-32.34000	8.45%
5	36.5	-31.2459	42.5	-32.56777	14.12%
6	40.3	-32.1061	43	-32.66936	6.28%
7	38.4	-31.6866	43.8	-32.82948	12.33%
8	42.1	-32.4856	44.2	-32.90844	4.75%
9	41.7	-32.4027	44.8	-33.02556	6.92%

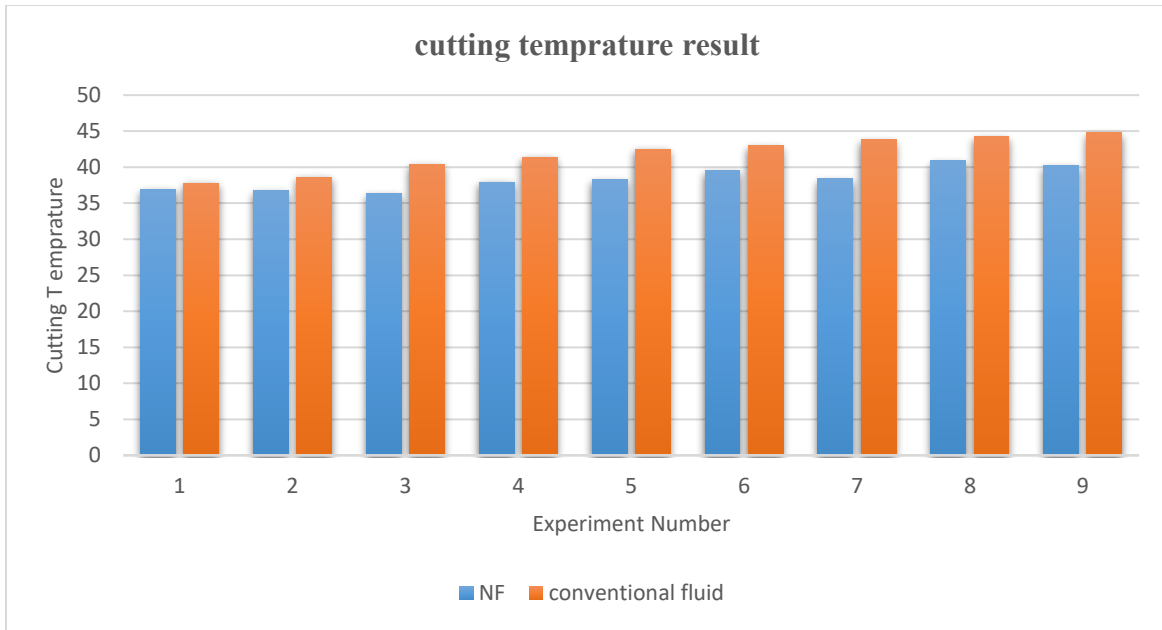


Figure 4:11 Comparison graph of the effect of NF and CF on cutting temperature

From the table and the comparison chart above, it is evident that nanofluid consistently led to lower turning temperatures when compared to commercial fluid across all nine experimental runs. This demonstrates the superior thermal performance of nanofluid, likely because of enhanced heat conductivity and improved lubrication characteristics imparted by the nano silica particles and aloe vera liquid in sunflower oil. The S/N ratios using the proposed fluid are consistently less negative compared to the conventional fluid, showing more stable performance with less variability because of noise factors.

The main effects plot *Figure 4:12* illustrates the individual effect of the spindle speed, feed rate, and nanofluid concentration on the machining temperature. As expected, higher spindle speeds and feed rates generally result in higher temperatures due to increased friction and deformation. However, the utilization of nanofluid shows a positive effect, especially at higher levels of particle concentration. This supports the conclusion that proper selection of process parameters in combination with nanofluid can successfully control heat generation during turning mild steel.

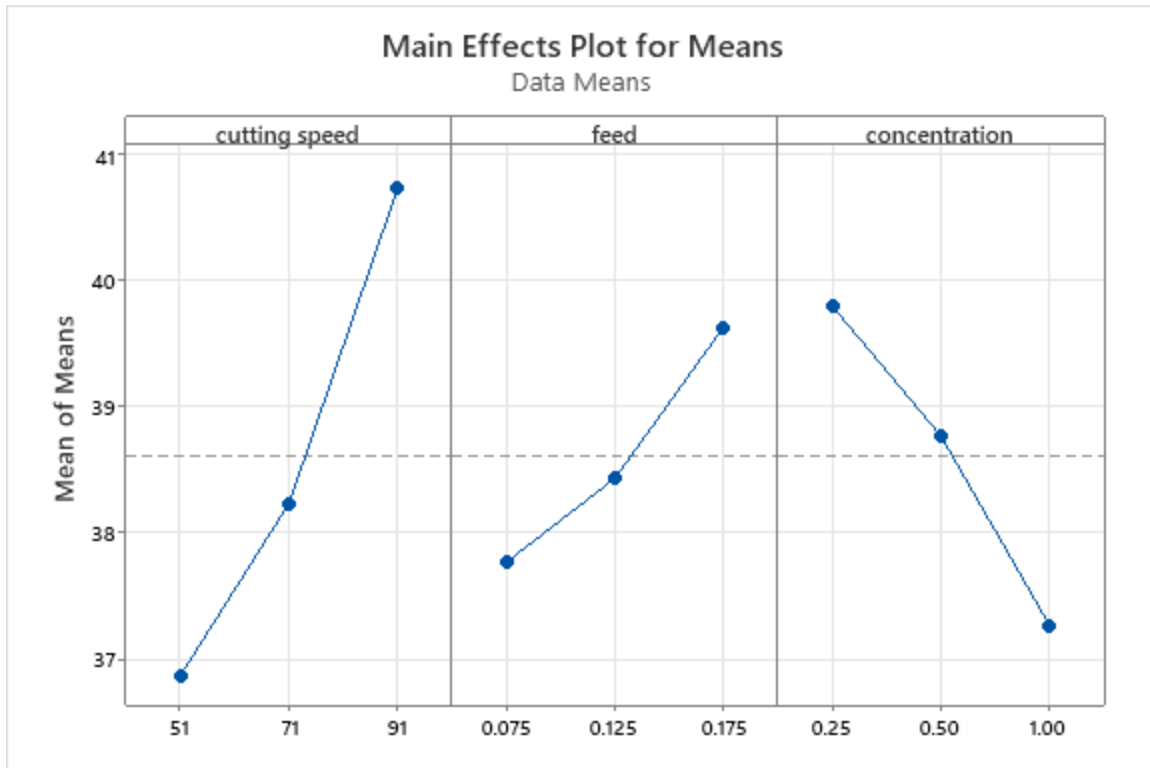


Figure 4:12 Main effects graph for input parameters on CT

4.4.2. Analysis of Variance (ANOVA) for Temperature

ANOVA was computed on the signal-to-noise (S/N) ratios for cutting temperature to compute the significance and relative contribution of every process. The objective is to find which factors most significantly influence heat rise during the CNC turning of mild steel material.

Table 4.9 Analysis of Variance for SN Ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution
cutting speed	2	1.13598	1.13598	0.56799	40.48	0.024	59.78 %
Feed	2	0.26042	0.26042	0.13021	9.28	0.097	13.75 %
concentration	2	0.47725	0.47725	0.23863	17.01	0.056	25.09 %
Residual Error	2	0.02806	0.02806	0.01403			1.4%
Total	8	1.90172					100 %

$$\text{Contribution percentage} = \frac{\text{Seq SS}}{\text{total Seq SS}} * 100\%$$

The analysis reveals that spindle speed has the greatest influence on cutting temperature, with a 59.78% of contribution and a statistically significant p-value of 0.024. This is expected, as higher cutting speeds increase friction and deflection at the interface between chip and tool, thereby raising temperature.

Nanofluid concentration follows as the second-highest influential parameter, contributing 25.09% to the variation in cutting temperature. The p-value of 0.056 slightly passes the 0.05 threshold, it is sufficiently close to practical significance. This further supports the thermal advantage of employing a nanofluid-enriched vegetable oil-based fluid to suppress heat. The feed rate contributed 13.75%, with a p-value of 0.097, showing a lesser impact on temperature compared to the other two parameters.

4.4.3. Selection of Optimal Levels and Regression Equation for Temperature

This section presents the identification of the optimal turning input variables for reducing cutting region temperature utilizing signal-to-noise (S/N) analysis and regression modeling. The "smaller-is-better" criterion is used, as lower temperatures are desired to reduce thermal distortion, improve the lifespan of the tool, and increase surface integrity during operation. A linear regression model was generated to establish a predictive function between cutting temperature (CT) and the three input parameters. The resulting regression equation is:

$$CT = 31.35 + 0.0967 \text{ cutting speed} + 18.67 \text{ feed} - 3.324 \text{ concentration}$$

Model summary: S = 0.534567, R-sq = 96.31%, R-sq(adj) = 94.10%, R-sq(pred) = 84.31%

From the model summary, the adjusted R² of 94.10% considers the number of input variables and confirms the equation remains strong even after adjusting for degrees of freedom. The R² value of 84.31% indicates that the model has good predictive capability on unseen data, which is better than the roughness prediction model. Also, from the *Table 4.10* The delta values indicate the sensitivity of each factor to cutting temperature. Accordingly, cutting speed has the biggest effect, followed by concentration, then feed.

Table 4.10 Response Table for S/N Ratios for cutting temperature

Smaller is better

Level	Cutting speed	Feed	concentration
1	-31.33	-31.54	-31.99

2	-31.64	-31.67	-31.76
3	-32.19	-31.95	-31.42
Delta	0.86	0.41	0.56
Rank	1	3	2

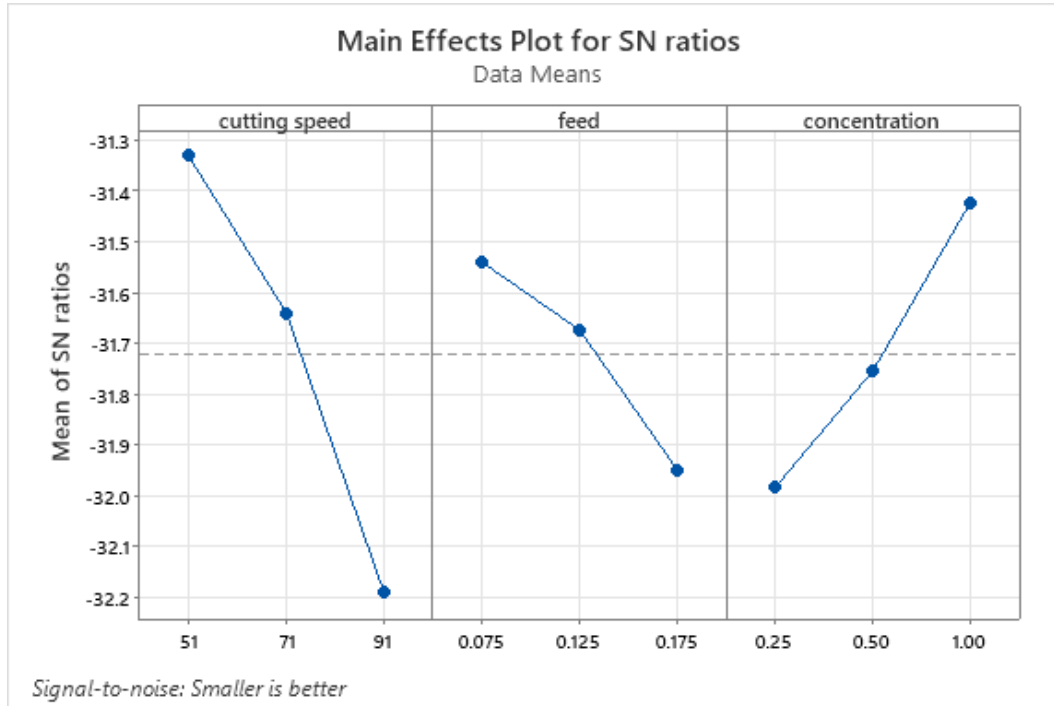


Figure 4:13 Main effects diagram for input parameters on temperature

Using the main effect graph for SN ratios and the S/N response table, the optimal parameter combination for minimal cutting temperature is at a cutting speed of 51 m/min, feed of 0.05 mm/rev, and particle proportion at wt. 1%. Accordingly, using the regression model, the predicted value is 35.3444 °C, which is the lowest cutting temperature that can be obtained using the parameters.

4.5. Multi-Response Optimization Result and Discussion

4.5.1. Grey Relational Analysis

In this study, a higher Grey Relational Grade (GRG) indicates that the associated experiment is closer to the ideal machining condition, i.e., lower SR and CT, and MRR. The ranking based on GRG values provides insight into which combination of input factors from the formulated trials yields the best balanced and efficient machining performance. First, the performance metrics were normalized to bring all results into a comparable range using Eq. 3.8 for SR and CT and rate Eq.

3.9 for the material removal. After that, deviation sequences were computed by subtracting actual values from one to measure the distance between ideal and actual responses. Finally, the grey relational coefficients (GRC) and GRG were computed to evaluate overall performance based on Eq. 3.10 and Eq. 3.11, respectively. The results of these steps are all tabulated in Table 4.11 and Table 4.12.

Table 4.11 Normalized response data and deviation sequence

Ex no.	Normalized data			Deviation Sequence		
	SR	MRR	CT	SR	MRR	CT
1	0.7963	0	0.91071	0.2037	1	0.08929
2	0.40741	0.20648	0.96429	0.59259	0.79352	0.03571
3	0.11111	0.56285	0.92857	0.88889	0.43715	0.07143
4	0.7963	0.16659	0.75	0.2037	0.83341	0.25
5	0.81482	0.61713	1	0.18519	0.38287	0
6	0	0.65936	0.32143	1	0.34064	0.67857
7	1	0.47777	0.66071	0	0.52223	0.33929
8	0.74074	0.5721	0	0.25926	0.4279	1
9	0.42593	1	0.07143	0.57407	0	0.92857

Table 4.12 GRC and GRG

Ex no.	Grey Relational Coefficients			Grey Relational Grade	
	SR (μm)	MRR (mm^3/s)	CT ($^\circ\text{C}$)	Grade	Grey order
1	0.71053	0.33333	0.84848	0.63078	9
2	0.45763	0.38654	0.93333	0.88875	4
3	0.36	0.53353	0.875	0.88427	5
4	0.71053	0.37498	0.66667	0.87609	6
5	0.72973	0.56633	1	1.14803	1
6	0.33333	0.59478	0.42424	0.67618	8
7	1	0.48913	0.59574	1.04244	2
8	0.65854	0.53885	0.33333	0.76536	7
9	0.46552	1	0.35	0.90776	3

From the result data, experimental run number 5 achieved the highest GRG of 1.14803, showing the best optimal parameter across all the desirable responses, followed by experiment numbers 7 and 9 with 1.04244 and 0.90776 GRG values, respectively. On the other side, the first experimental trial resulted in the lowest GRG, which is 0.63078, making it the least favorable in terms of combined machining effectiveness. These rankings provide a basis for selecting the best set of parameters that balances surface roughness, MRR, and cutting temperature.

Table 4.13 Response table for GRG

Parameters	Levels		
	1	2	3
Speed	0.80127	0.9001	0.90518
Feed	0.84977	0.93405	0.82273
Concent.	0.69077	0.89087	1.02491

From the table for GRG, the best set of parameters for effective overall performance is:

- Cutting Speed: Level 3 (91 m/min)
- Feed Rate: Level 2 (0.1 mm/rev)
- Silica proportion: Level 3 (1 wt.%)

→ Optimal Setting: V3F2C3

The GRA rankings also aligned well with observed trends in individual response parameters, reinforcing the reliability of the method in multi-objective optimization.

4.5.2. TOPSIS

In this evaluation, to find the objective weights of each output variable, the Entropy Weighting Method was applied. Initially, the experimental data were normalized using *Eq. 3.17* and *Eq. 3.18* to construct the proportion matrix, as shown in *Table 4.14*. This stage of computation ensures comparability across responses with different units' scales. Next to that, the entropy values for each response were computed by applying *Eq. 3.19* to determine the inherent information and uniformity in the dataset. From the entropy result, the degree of diversification was calculated by subtracting entropy from one, reflecting the contrast intensity of each criterion. Finally, the objective weights for SR, MRR, and CT were derived according to their relative diversification and are tabulated in *Table 4.15*. This objective weighting approach ensures that the influence of

each response in multi-objective optimization reflects the data distribution rather than subjective judgment.

Table 4.14 Entropy weighing Method normalized and proportion matrix result data

<i>Normalization</i>			<i>Proportion matrix</i>		
<i>SR</i>	<i>MRR</i>	<i>CT</i>	<i>SR</i>	<i>MRR</i>	<i>CT</i>
0.796296	0	0.910714	0.156364	0	0.16242
0.407407	0.20648	0.964286	0.08	0.048444	0.171975
0.111111	0.562848	0.928571	0.021818	0.132054	0.165605
0.796296	0.166592	0.75	0.156364	0.039085	0.133758
0.814815	0.617126	1	0.16	0.144788	0.178344
0	0.659357	0.321429	0	0.154696	0.057325
1	0.477767	0.660714	0.196364	0.112092	0.117834
0.740741	0.572102	0	0.145455	0.134225	0
0.425926	1	0.071429	0.083636	0.234617	0.012739

Table 4.15 Entropy and final weight of each response

Criterion	Entropy (E)	Diversification (1 – E)	Final Weight
SR	0.895037	0.104963	0.32162
MRR	0.893963	0.106037	0.32491
CT	0.88464	0.11536	0.35347

- SR weighted (32.16%)
- MRR weighted (32.49%)
- CT has the highest importance (35.35%), meaning it varies most between the trials

Ideal Solution (best): v^+ = Minimum Ra, Maximum MRR, Minimum Temp

Negative Ideal (worst): v^- = Maximum Ra, Minimum MRR, Maximum Temp

Following the computation of response weights using the Entropy Weighting Method (EWM), the TOPSIS analysis was conducted to rank the experimental alternatives. Initially, the raw response data were normalized using *Eq. 3.12* to transform the data into a dimensionless scale. The weighted normalized data were then calculated using *Eq. 3.13* by multiplying the normalized matrix with the entropy-derived weights as tabulated in *Table 4.16*.

Next, the separation measures were computed using *Eq. 3.14* and *Eq. 3.15* to compute the Euclidean distance of every alternative from the ideal solution (positive ideal) and the negative ideal solution, respectively. Finally, the closeness coefficient (CC) for each alternative was calculated using *Eq. 3.16*, which quantifies the degree to which each alternative approaches the ideal solution as tabulated in the *Table 4.17*. A higher closeness coefficient reflects a more desirable alternative.

Table 4.16 Normalized and weighted normalized value for TOPSIS analysis

<i>Ex. No.</i>	Normalized			Weighted normalized value		
	<i>SR</i>	<i>MRR</i>	<i>CT</i>	<i>SR</i>	<i>MRR</i>	<i>CT</i>
1	0.232777	0.166556	0.32053	0.074866	0.054116	0.1133
2	0.368564	0.251109	0.31879	0.118537	0.081588	0.11268
3	0.47202	0.360335	0.31532	0.151811	0.117076	0.11146
4	0.232777	0.180692	0.32922	0.074866	0.058709	0.11637
5	0.226311	0.415229	0.33269	0.072786	0.134912	0.1176
6	0.510816	0.454224	0.34311	0.164289	0.147582	0.12128
7	0.161651	0.226587	0.33356	0.05199	0.07362	0.1179
8	0.252175	0.308141	0.35527	0.081105	0.100118	0.12558
9	0.362098	0.470835	0.34919	0.116458	0.152979	0.12343

Table 4.17 Separation Measures, Closeness Coefficient, and Rank

S⁺	S⁻	CC	Rank
0.101492	0.090262	0.470719	5
0.097605	0.047534	0.327507	7
0.106081	0.018848	0.150867	8
0.09713	0.089896	0.48066	4
0.028224	0.091852	0.764947	1
0.112857	0.004375	0.037323	9
0.07962	0.112561	0.585702	2

0.061979	0.083184	0.573038	3
0.06557	0.047889	0.42208	6

According to the TOPSIS results:

- The first rank is experimental trial 5, which achieved the highest closeness coefficient of 0.7649, indicating it is the most ideal parameter combination considering all responses.
- Following experiments 7 and 8 ranked second and third, respectively, also showing strong closeness to the ideal solution.
- Experiment 6 had the lowest closeness coefficient, suggesting it performed the least optimally among the tested conditions.

Table 4.18 Response table for closeness coefficient

Response Table for Closeness Coefficient			
Parameters	1	2	3
Speed	0.316364	0.427643	0.52694
Feed	0.51236	0.555164	0.203423
Conc.	0.36036	0.410082	0.500506

From the *Table 4.18* For the closeness coefficient, the best set of input parameters for the best overall performance is:

- Cutting speed: Level 3 (91 m/min)
- Feed: Level 2 (0.125 mm/rev)
- Concentration: Level 3 (1 wt.%)

→ Optimal Setting: V3F2C3

4.5.3. Comparison of GRA and TOPSIS Results

To verify the reliability of the two multi-objective optimization processes, the output from GRA and TOPSIS was compared. Both approaches were applied to compute the effect of turning parameters on the three key performance indicators: CT, MRR, and SR.

As observed from *Table 4.13* and *Table 4.18*, which presents the response tables for GRG and CC, respectively, both multi-objective optimization methods identified the same optimal parameter combination or settings, which is V3F2C3.

Table 4.19 Grey Relational Grades and Relative Closeness values along with their ranks

Experiment	GRG (GRA)	GRA Rank	C ⁺ (TOPSIS)	TOPSIS Rank
1	0.63078	9	0.470719	5
2	0.88875	4	0.327507	7
3	0.88427	5	0.150867	8
4	0.87609	6	0.48066	4
5	1.14803	1	0.764947	1
6	0.67618	8	0.037323	9
7	1.04244	2	0.585702	2
8	0.76536	7	0.573038	3
9	0.90776	3	0.42208	6

From the above table, it is evident that experiment 5 ranked first in both approaches, clearly confirming it as the optimal parameter setting. In experiment trial 7, they also show good agreement, ranking second in both TOPSIS and GRA. Experiment 6 was ranked lowest by both methods consistently, indicating poor performance across all metrics. In some of the experiments, some variation occurred, such as in experiment 1, which ranked 9th in GRA but 5th in TOPSIS, and experiments 2, 3, and 9, which performed slightly better in GRA than in TOPSIS.

These small differences are expected because of the difference in computational philosophies of both methods, namely GRA and TOPSIS. GRA utilizes normalized distance-based relational coefficients, while TOPSIS considers geometric closeness to ideal and non-ideal solutions. Also, this occurred due to a difference in weighting strategies, at which GRA applies equal weighting, while TOPSIS with entropy adjusts weights based on the inherent variability and informativeness of each performance measure. Ignoring these differences, both methods converged on the same top-performing experimental trials that only matter, showing robust agreement and reinforcing the reliability of the optimization process.

4.6. Confirmation Test

To evaluate the reliability and practical applicability of the optimal machining factors computed using the Taguchi and GRA/TOPSIS optimization methods, a confirmation test was conducted. A verification experiment of the best setting of parameters is performed to confirm the reliability of

the selected machining settings obtained from optimization. Machining was conducted under optimal and random parameter settings, and the experimental results were compared with predicted values to assess the reliability of the optimization process, which is tabulated below.

Table 4.20 Error analysis for verification of predicted and experimental results

Metrics	Parameters	Experiment Result	Predicted	Error %
Surface	Optimal, MRO, V ₃ f ₂ C ₃	1.5	1.84	18.4
roughness (µm)	Optimal, Taguchi, V ₃ f ₁ C ₃ ,	1.25	0.915	36.61
	Random parameters, V ₂ f ₃ C ₁	3.95	3.68	7.34
Material	Optimal, MRO, V ₃ f ₂ C ₃	103.4	114.2	9.45
removal rate (mm ³ /s)	Optimal, Taguchi, V ₃ f ₃ C ₃	134.4	140.65	4.38
	Random parameters, V ₂ f ₁ C ₂	54.12	58.11	6.86
Cutting	Optimal, MRO, V ₃ f ₂ C ₃	37.3	39.16	4.75
temperature (°C)	Optimal, Taguchi, V ₁ f ₁ C ₃	35.8	34.68	3.23
	Random parameters, V ₁ f ₃ C ₃	36.9	36.2	1.93

The results indicate that a relatively small error has been observed except for optimal surface roughness, with the highest error values. Even when predictive errors were presented, particularly for roughness under Taguchi optimal conditions with an error value of 36.61%, it is possibly because of surface finish sensitivity to minor process deviations that the method successfully identified parameter combinations that enhanced machining performance over unoptimized settings. Random parameter setting was included for validation and produced relatively low prediction errors, reinforcing the model's strength and health. These results validate that Taguchi, TOPSIS, and GRA optimization methods are not only theoretical tools but also practically impactful, capable of delivering measurable benefits in real-world industrial scenarios.

Chapter five

5. Conclusion and Recommendation

5.1. Conclusion

This study aimed to develop and analyze the performance of a novel cutting fluid composed of sunflower oil and aloe vera base fluid blended with SiO₂ nanoparticles, intended to increase machining effectiveness during the CNC machining of mild steel. A systematic experimental investigation was conducted using Taguchi design, and two multi-objective optimization approaches, namely GRA and TOPSIS, were utilized to find the optimal turning settings. Key performance metrics, including SR, MRR, and cutting temperature, were analyzed to validate the efficacy of the proposed machining fluid. The following conclusions summarize the major outcomes and their associated implications.

1. The characterization of the formulated biomodified nanofluid confirms that the sample fluid having 1 wt% of silica powder provides the best combination of lubrication with dynamic viscosity increased from 41 to 52.2 mPa·s at 35 °C, near neutral pH of 6.2 ensuring operators safety, and same stability level comparing with the other samples, but dispersion processes may require addition of surfactants and increased ultrasonication time for long term stability.
2. The effectiveness of the proposed Nanofluid in:
 - Surface roughness was reduced, ranging from 4 to 22.84% comparing to using conventional fluid, and an average of 10.28% improvement across all trials due to the polishing and lubricating effect of the fluid.
 - Material removal rate was increased by an average of 7.2% comparing to using a conventional one, peaking at 137.7 mm³/s (Experiment 9), and a slight reduction in two of the experimental trials, probably due to the sensitivity of the measurement and lower contribution of the employed sample fluid.
 - Also, cutting temperature consistently reduced, ranging from 2 to 14% utilizing the nano fluid, and an average of 7.6%, due to the fluid's improved thermal characteristics.
3. Effect of input variables on:
 - When evaluating surface roughness, feed rate was dominant with 75.91% contribution, which is very significant, following spindle speed and particle concentration with contributions of 14.53% and 6.11%, respectively.

- ANOVA analysis for MRR shows that feed, cutting speed, and silica concentration have contributions of 54.06%, 37.36%, and 8.5%, respectively; in addition to that, all the parameters have a significant effect on MRR.
 - From the analysis for cutting temperature, cutting speed (59.78%) was the most influential and significant factor, followed by silica concentration and feed rate, with contributions of 25.09% and 13.75%, respectively.
4. Optimal setting of parameters:
 - For minimal SR, it was identified to be 91 m/min cutting speed (CS), 0.075 mm/rev feed, and 1wt% of silica concentration (v3f1c3). Also, regression equations with a prediction capacity of 60.34% were formulated.
 - For maximum production capacity, which is the material removal rate is found to be at 91 m/min of cutting speed, at 0.125 of feed, and with 1wt% of silica concentration (v3f3c3). Also, a linear regression equation with the highest prediction performance of 89.67% was generated.
 - For minimal cutting temperature, the optimal combination was found to be 51 m/min of CS, feed rate at 0.075 mm/rev, and 1 wt% of nanoparticle concentration (v1f1c3). And a corresponding linear regression model was formulated with a prediction accuracy of 84.31%.
 5. Validating experiments compared to predicted values shows an average of 7% error for MRR, 3.3% error for temperature prediction over actual values, and the highest error value for surface roughness was recorded up to 37%, due to the very low predicting capacity of the model and sensitivity to minor process deviations.
 6. From both multi-objective optimization methods, namely GRA and TOPSIS, it is evident that experiment trial 5 is best for balanced performance, followed by experiment 7. However, from the response data, it is identified that a speed of 91 m/min, a feed of 0.125 mm/rev, and a 1 wt% silica concentration (V3F2C3) are optimal parameter settings for turning of mild steel using the proposed nanofluid.

5.2. Recommendation

According to the findings of this research, it is recommended to adopt a nanofluid composed of 1 wt.% SiO₂ nanoparticles dispersed in a sunflower oil and aloe vera (SFO: AV) blend at a 70:30 ratio. This formulation showed higher performance in terms of surface finish, MRR, and thermal

control during the turning of mild steel. For finishing operations, a CS of 91 m/min combined with a feed rate of 0.075 mm/rev is suggested to decrease SR.

To ensure optimal cutting efficiency, the proposed machining liquid should include surfactants or dispersants as one of its constituents, such as SDC (sodium dodecyl di sulphate), span 80, and other additives, and the agitation time should be increased. In addition to that, ultrasonication time should be increased for improved stability. This maintains a uniform suspension of nanoparticles within the primary fluid, enhancing heat dissipation, lubrication, and overall cutting efficiency. An impeller may also be coupled to a small electric motor, ensuring the nanofluid remains uniform using slow rotation, as proposed by previous researchers [58]. The performance of different nanofluids is directly affected by the size of the nanoparticles [34]. Therefore, the size of the nano silica powder used should be optimized to increase the effectiveness of the synthesized fluid

5.3. Future Works

Further investigations are necessary to assess the full capacity of this biomodified nanofluid. Also, for cumulative improvements in thermal property and lubrication, studies should be conducted on using hybrid nanoparticles like $\text{SiO}_2\text{-Al}_2\text{O}_3$, $\text{SiO}_2\text{-TiO}$, and other potential mixtures. In the other way, broader process parameter expansion and addition, including higher silica concentration, higher cutting speed range, varying depth of cut, varying MQL flow rate, and other working conditions, can be conducted. Nonlinear regression with interaction terms and the use of AI optimization codes, such as genetic algorithm (GA) and artificial neural network (ANN) can enhance prediction and optimization accuracy, so it is worth exploring.

Essentially, microbial growth resistance of the prepared fluid should be evaluated to examine health and safety in long-term industrial use. Additionally, evaluating the performance in different materials and machining operations, such as milling and drilling, will verify its versatility across diverse production conditions. For extended tool and machine tool life, corrosion inhibition properties of the fluid should also be examined. Lastly, an economic evaluation should be performed to validate its feasibility in a mass production application. This research positions the machining fluid as a high-performance, eco-friendly alternative to conventional ones, capable of improving productivity while minimizing environmental and operators' health impact.

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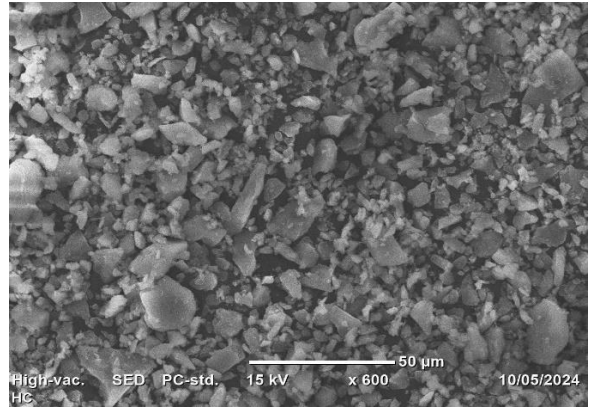
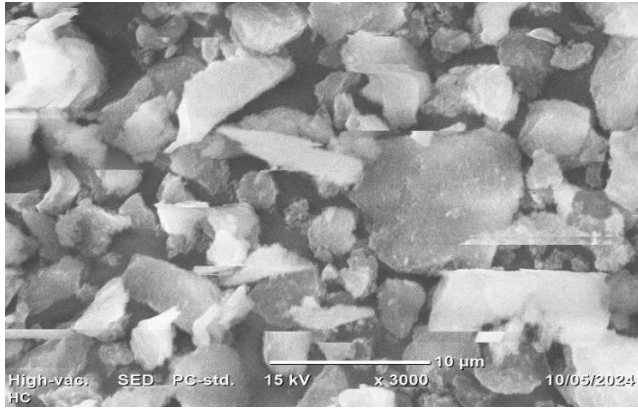
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Appendix

1. Silica Nano powder SEM result from the researchers



3. Workpiece material preparation



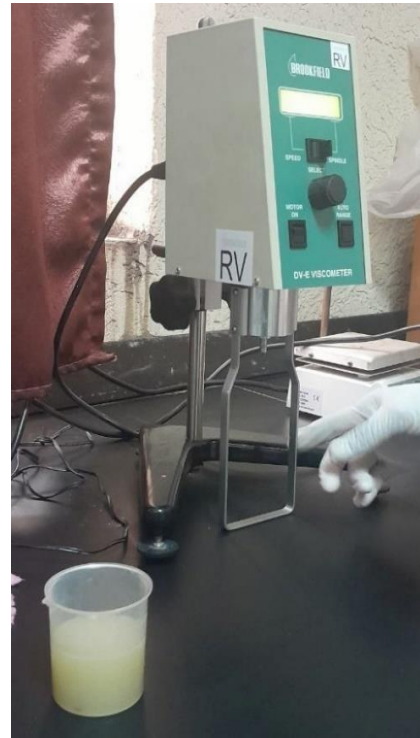
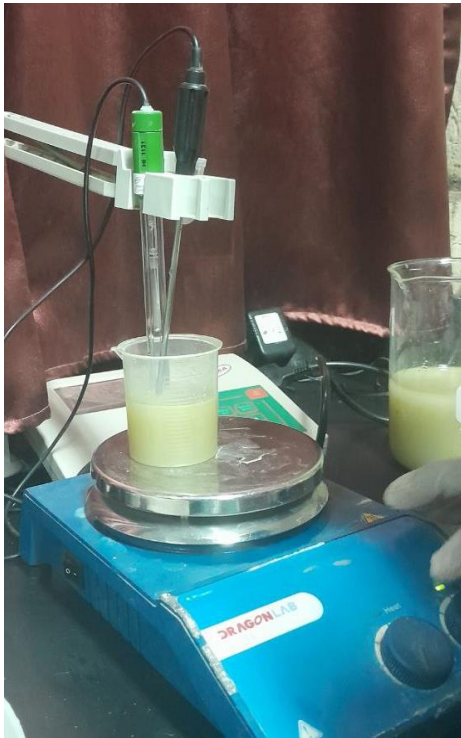
4. Aloe vera plant harvest and gel extraction



5. Fluid preparation process and instruments



6. Fluid characterization ayder pharma analysis lab



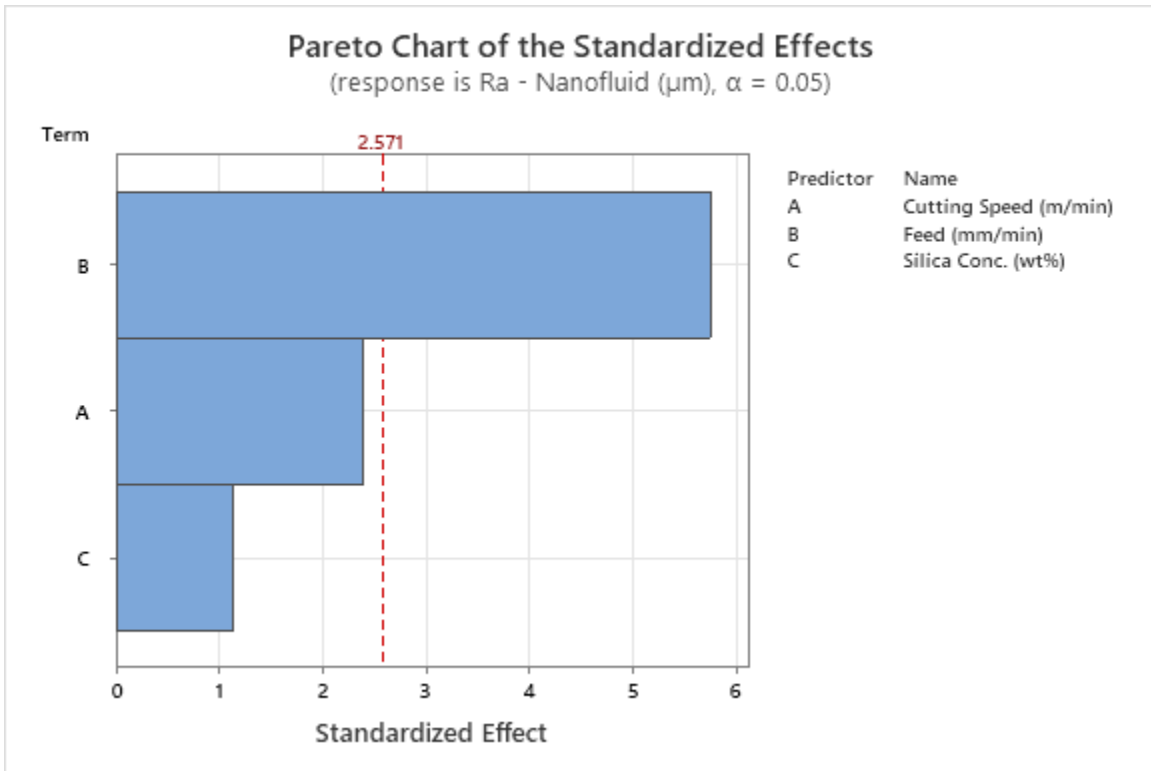
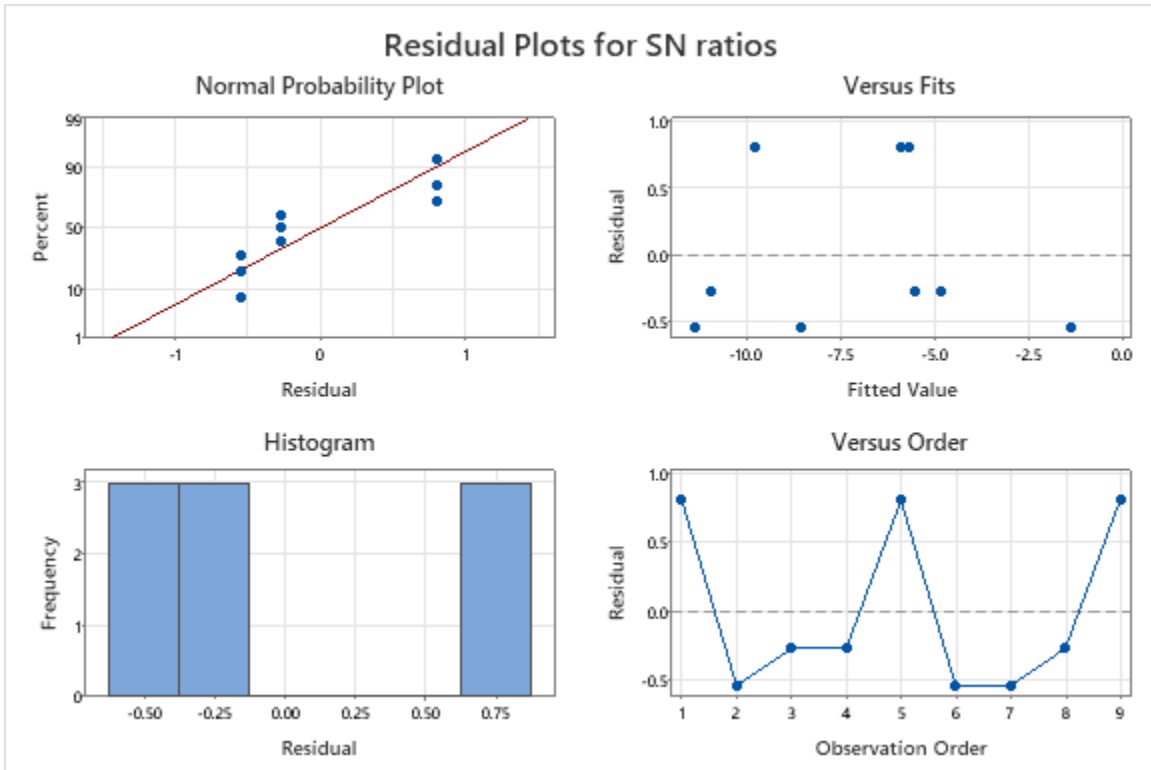
7. Viscosity result

VISCOSITY TEST REPORT				DATE: 21 / 04 / 2025		TO: Yared Selemon Head, Dept. of Pharmaceutical Analysis & Quality Assurance				
				BY: Hayelom Fissaha						
TEST INFORMATION: this experiment has been taken using pharma analysis laboratory standard RV DVE Brookfield viscometer to experimentally investigate the property of nanofluids and base fluids prepared by the applicant										
SAMPLE	DESCRIPTION	SPINDLE	RPM	DIAL READING % TORQUE	FACTOR	VISCOSITY cP	SHEAR RATE	TEMP °C	TIME	Note
1	Sunflower oil	02	100	23 %		53.2		25°	62 s	
		02	100	18.2 %		32.8		35°	58 s	
		02	100	15.1 %		22.5		45°	47 s	
2	Base fluid	02	100	21.1 %		54.4		25°	59 s	
		02	100	17.9 %		30.7		35°	60 s	
		02	100	15.5 %		15.2		45°	65 s	
3	Sample 1	02	100	23.2 %		57.2		25°	68 s	
		02	100	19.4 %		41		35°	60 s	
		02	100	16.1 %		25.5		45°	58 s	
4	Sample 2	02	100	23.2 %		62.8		25°	47 s	
		02	100	19.9 %		46.3		35°	69 s	
		02	100	14.5 %		31		45°	63 s	
5	Sample 3	02	100	22.5 %		69.3		25°	49 s	
		02	100	18 %		52.2		35°	52 s	
		02	100	15.3 %		34.6		45°	58 s	
CONCLUSIONS: according to the standard and procedure provided by the manufacturer and applicant the dynamic viscosity have been examined as tabulated above.										

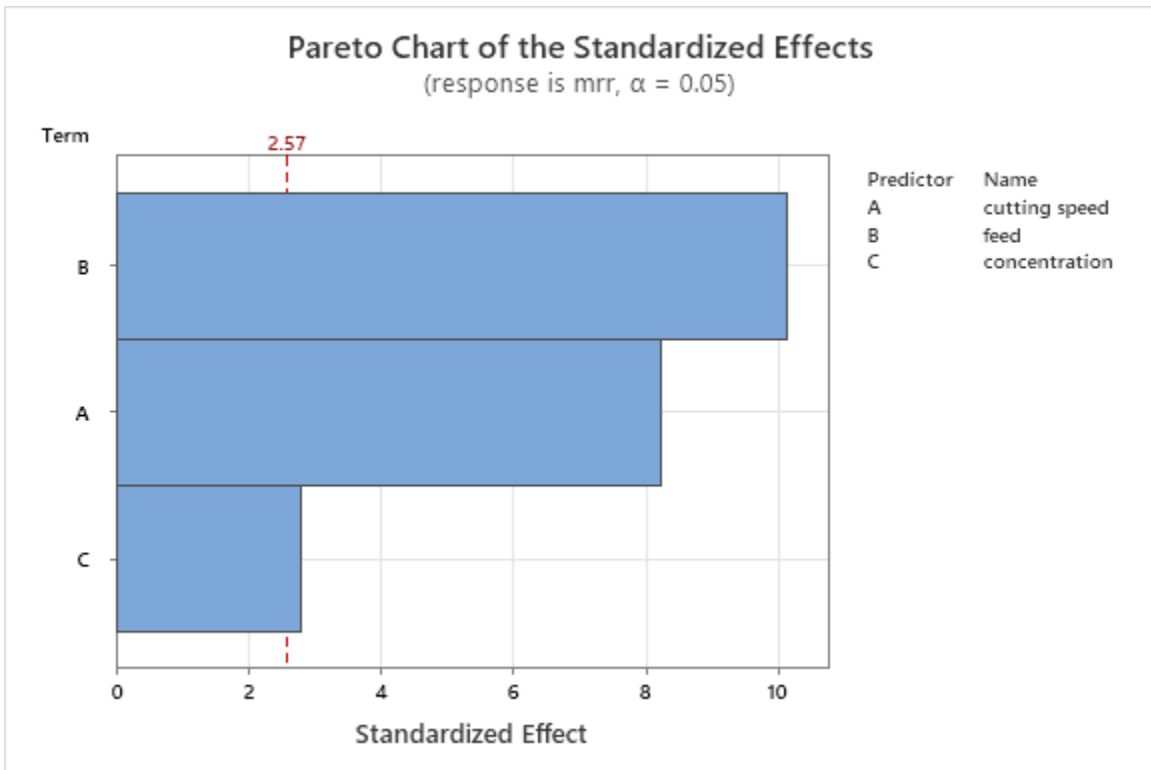
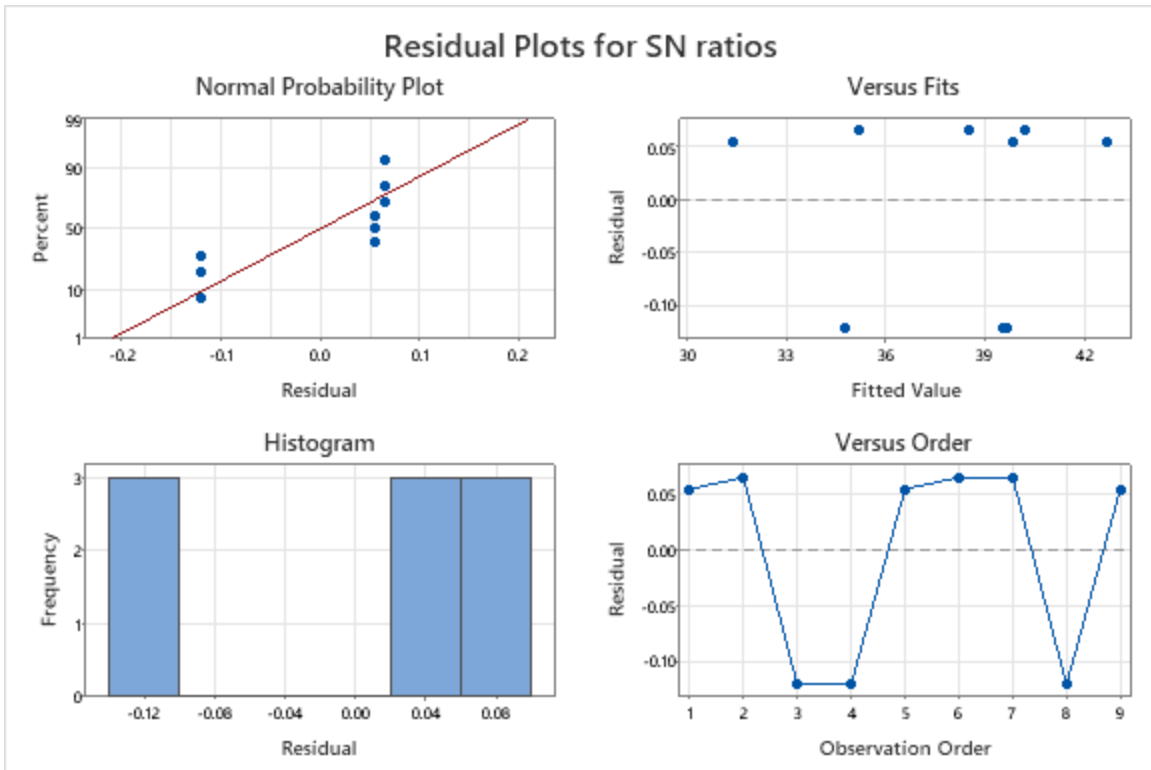
8. Machining Environment



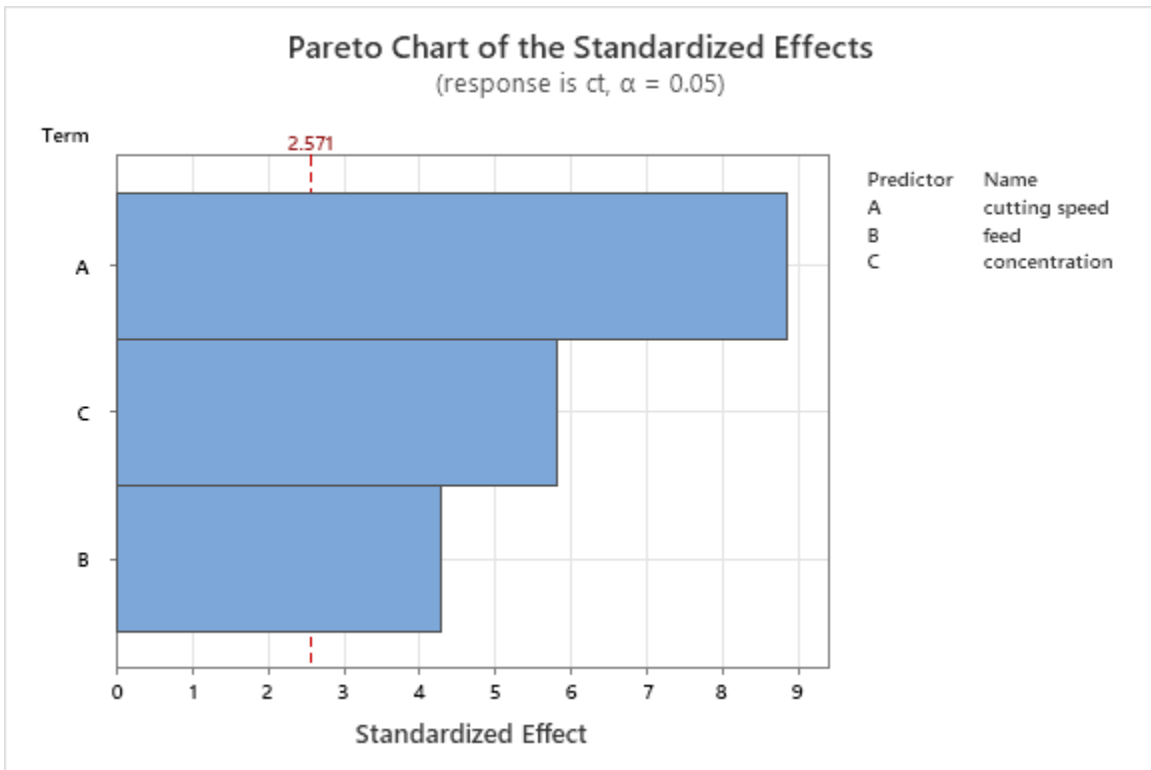
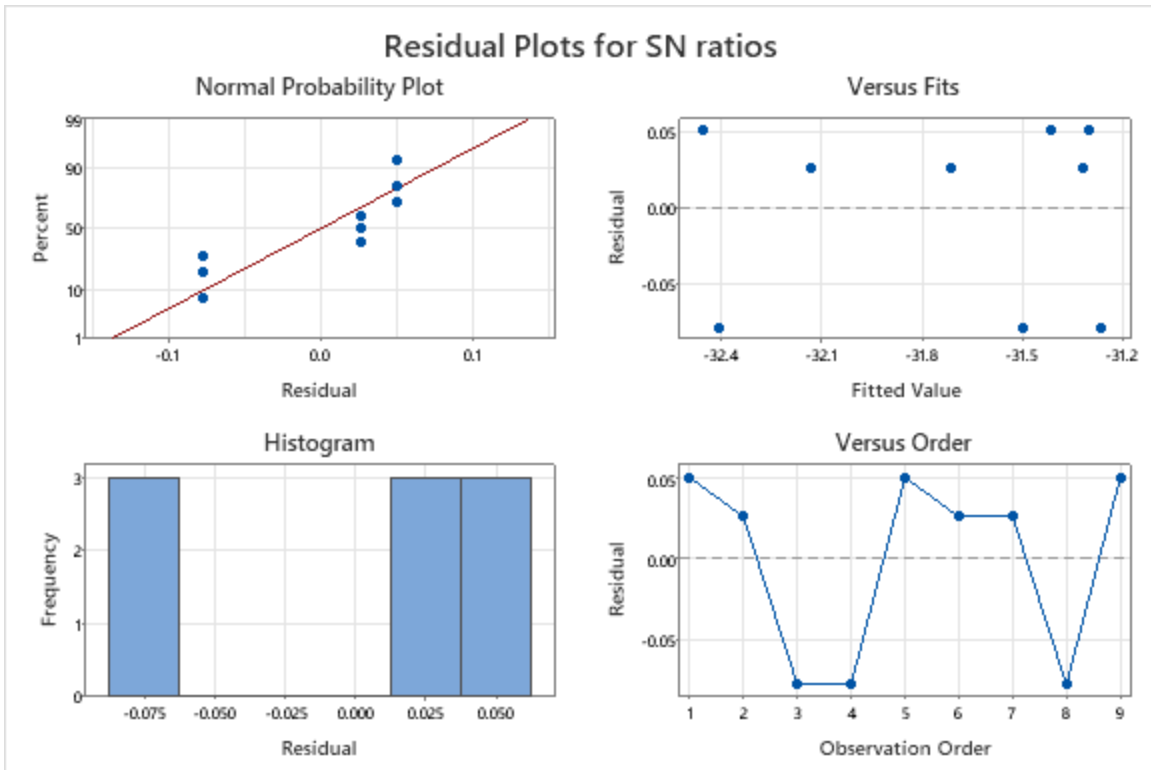
9. Residual plots for S/N ratios and pareto chart of the standardized effect



For surface roughness



For material removal rate



For cutting temperature