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Sustainable Turning Performance of AISI 1045 Steel under Nanofluid Minimum Quantity Lubrication: An Integrated Assessment of Surface Roughness, Tool Wear, Specific Cutting Energy, and Carbon Emission

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ABSTRACT

With the growing demand for sustainable machining, this has focused interest on finding sustainable alternatives to traditional cutting that is energy consuming, fast tool change and has negative environmental impact. A cleaner method is Nanofluid minimum quantity lubrication (MQL) which involves using cutting fluid in reduced quantities to achieve appropriate lubrication and cooling. In this study, the surface roughness, tool wear, material removal rate, cutting power, specific cutting energy and carbon emission of the nanofluid-MQL process were studied. The effect of cutting speed, feed rate, depth of cut and lubrication condition on the aspect of quality of machining, degradation of tool and energy and environmental performances are analyzed by using a narrative mathematical model. The results revealed that machining performance can be improved using nanofluid-MQL, as it provides excellent lubrication, lower friction, and more stable chip formation, which results in lower surface roughness, lower tool wear, and lower specific cutting energy. The study has developed a comprehensive sustainable machining model that connects machining parameters with tool life, surface integrity, energy usage and carbon emission, which can facilitate the realization of cleaner production and more energy efficient manufacturing systems.

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1. INTRODUCTION

Sustainable machining is an important issue in modern mechanical engineering because manufacturing processes must produce accurate components while reducing energy consumption, material waste, cutting fluid use, and environmental impact. Conventional machining often relies on flood cooling to reduce cutting temperature and friction [1], [2], [3]. However, excessive cutting fluid use may increase operating cost, waste treatment requirements, and environmental burden [4], [5]. A recent review on sustainable machining explains that green machining technologies are increasingly studied to reduce the environmental impact of conventional cutting fluids and improve economic, environmental, and social sustainability in manufacturing systems [6], [7].

Turning is one of the most widely used machining processes for producing cylindrical components. In turning, the cutting tool removes material from a rotating workpiece to obtain the desired diameter, surface finish, and dimensional accuracy. The process performance is influenced by cutting speed, feed rate, depth of cut, tool geometry, workpiece material, lubrication condition, and machine tool rigidity. Poor selection of cutting parameters may increase surface roughness, tool wear, vibration, cutting force, energy consumption, and production cost [8], [9].

AISI 1045 steel is widely used in mechanical components because it provides moderate strength, machinability, and availability. This steel is commonly used for shafts, gears, bolts, machine parts, and automotive components. However, turning of medium carbon steel still requires proper control of cutting temperature, friction, and tool wear to obtain acceptable surface quality and energy efficiency [10], [11].

Minimum quantity lubrication, or MQL, is a machining lubrication strategy that delivers a very small amount of cutting fluid into the cutting zone in the form of mist. Compared with flood cooling, MQL reduces fluid consumption and can improve lubrication at the tool–chip interface. The use of nanofluid in MQL has received attention because nanoparticles can improve thermal conductivity, anti-friction behavior, and load-carrying capacity of the lubricant. A 2026 review reports that nanofluid minimum quantity lubrication can reduce cutting force, torque, cutting temperature, tool wear, and surface roughness compared with dry cutting, conventional MQL, and flood cooling in many machining cases.

Recent studies also show that nano-MQL can improve machining performance. For example, TiC-based nano-MQL in AISI 1040 turning improved surface quality, decreased energy consumption, reduced cutting forces, minimized tool wear, and supported stable chip-breaking behavior. Other studies on hybrid nanofluid MQL reported reductions in specific energy and surface roughness, indicating that lubrication strategy can influence both productivity and sustainability indicators.

Although many studies evaluate surface roughness, tool wear, or energy consumption separately, a complete sustainable machining analysis should connect machining quality, tool condition, material removal rate, energy efficiency, and carbon emission. Therefore, this study proposes an integrated assessment framework for turning AISI 1045 steel under nanofluid MQL [12]. The novelty of this study lies in the integration of machining performance, energy-based indicators, and emission estimation in one mechanical engineering framework.

Literature Review and Theoretical Framework

Sustainable Machining

Sustainable machining refers to the design and operation of machining processes that reduce environmental impact while maintaining productivity, product quality, and economic feasibility. In practical machining, sustainability can be evaluated from several indicators, including cutting fluid consumption, energy consumption, tool life, surface quality, waste generation, and carbon emission [12], [13]. The main challenge in sustainable machining is balancing productivity and environmental performance. A high material removal rate can reduce machining time, but it may increase cutting force, tool wear, and power consumption if the cutting parameters are not properly selected. Conversely, conservative cutting parameters may reduce tool wear but increase production time and energy consumption per component. Therefore, sustainable machining requires an integrated analysis of process quality, energy efficiency, and tool performance.

Minimum Quantity Lubrication and Nanofluid MQL

Minimum quantity lubrication supplies a small amount of lubricant to the cutting zone using compressed air [14], [15]. The lubricant mist reaches the tool–chip and tool–workpiece interfaces, where it reduces friction and heat generation. This lubrication mechanism can improve tool life and surface finish while reducing cutting fluid consumption. Nanofluid MQL uses nanoparticles dispersed in a base lubricant. The nanoparticles may improve heat transfer, lubrication film strength, and tribological performance. In the cutting zone, the nanofluid can reduce direct contact between tool and chip, decrease friction, and lower cutting temperature. This condition can reduce tool wear and improve surface quality.

The mechanism of nanofluid MQL can be explained through three main effects. First, the lubrication effect reduces friction at the tool–chip interface. Second, the cooling effect reduces cutting temperature by improving heat removal. Third, the rolling or polishing effect of nanoparticles may reduce microscopic surface damage during cutting. These effects make nanofluid MQL relevant for sustainable machining research.

Cutting Speed

Cutting speed represents the tangential speed between the rotating workpiece and the cutting tool [16]. In turning, cutting speed can be calculated using the equation:

$$V_c = \frac{\pi D N}{1000}$$

In this equation, $V_c$represents cutting speed in meters per minute. The variable Drepresents the workpiece diameter in millimeters, while Nrepresents spindle speed in revolutions per minute. The value 1000 is used to convert millimeters into meters. This equation means that cutting speed increases when the workpiece diameter or spindle speed increases. Cutting speed influences heat generation, tool wear, chip formation, and surface quality. Higher cutting speed may improve productivity, but it can also increase cutting temperature and accelerate tool wear. Therefore, cutting speed must be selected carefully to achieve a balance between productivity and tool life.

Feed Rate

Feed rate describes the axial movement of the cutting tool per revolution of the workpiece. In turning, feed rate is commonly expressed in millimeters per revolution [17], [18]. A higher feed rate allows faster material removal, but it may increase surface roughness because the tool leaves deeper feed marks on the machined surface.

The theoretical surface roughness in turning can be approximated using the equation:

$$R_a = \frac{f^2}{32 r_e}$$

In this equation, $R_a$represents the average surface roughness, $f$represents the feed rate, and $r_e$represents the tool nose radius. This equation means that surface roughness increases with the square of feed rate and decreases when the tool nose radius becomes larger. Therefore, feed rate has a strong influence on surface finish. For example, if the feed rate is 0.20 mm/rev and the tool nose radius is 0.8 mm, the theoretical surface roughness is calculated as:

$$R_a = \frac{0.20^2}{32(0.8)}$$

$$R_a = \frac{0.04}{25.6} = 0.00156 \text{ mm}$$

Since 0.00156 mm is equal to 1.56 µm, this result means that the expected surface roughness is approximately 1.56 µm under ideal geometric conditions. In actual machining, the measured roughness may be higher because of vibration, tool wear, built-up edge, material adhesion, and thermal effects.

Depth of Cut

Depth of cut represents the thickness of material removed from the workpiece in the radial direction [19]. In turning, depth of cut affects material removal rate, cutting force, cutting temperature, and machine power. A larger depth of cut increases productivity because more material is removed in one pass. However, it also increases mechanical load on the tool and machine. Depth of cut must be selected according to tool strength, workpiece material, machine rigidity, and surface quality requirements. If the depth of cut is too high, the cutting process may become unstable and produce excessive tool wear. If the depth of cut is too low, productivity may decrease because more machining passes are required.

Material Removal Rate

Material removal rate describes the volume of material removed per unit time. It is an important productivity indicator in machining [20], [21]. In turning, material removal rate can be calculated using:

$$MRR = V_c \times f \times a_p$$

In this equation, MRRrepresents material removal rate. The variable $V_c$represents cutting speed, $f$represents feed rate, and $a_p$represents depth of cut. This equation means that productivity increases when cutting speed, feed rate, or depth of cut increases. For example, if the cutting speed is 150 m/min, the feed rate is 0.20 mm/rev, and the depth of cut is 1.0 mm, the material removal rate can be interpreted as increasing proportionally with these three parameters. In practical calculation, unit consistency must be maintained so that the result is expressed in cubic millimeters per minute or cubic centimeters per minute. A higher material removal rate is desirable for productivity. However, it may increase cutting force and power demand. Therefore, material removal rate should be analyzed together with surface quality, tool wear, and energy consumption.

Cutting Force and Cutting Power

Cutting force is the mechanical force required to remove material from the workpiece. Cutting power represents the rate of energy used during cutting [22], [23]. Cutting power can be calculated using:

$$P_c = F_c \times V_c$$

In this equation, $P_c$represents cutting power, $F_c$represents the main cutting force, and $V_c$represents cutting speed. This equation means that cutting power increases when cutting force or cutting speed increases. If cutting force is measured in newtons and cutting speed is converted into meters per second, the resulting power is expressed in watts. For example, if the cutting force is 420 N and the cutting speed is 150 m/min, the cutting speed must first be converted into meters per second by dividing 150 by 60, giving 2.5 m/s. The cutting power is then calculated as:

$$P_c = 420 \times 2.5 = 1050 \text{ W}$$

This value means that the cutting process requires approximately 1.05 kW of mechanical cutting power. In sustainable machining, reducing cutting force can reduce power demand and improve energy efficiency.

Specific Cutting Energy

Specific cutting energy represents the amount of energy required to remove a unit volume of material. It is an important indicator for evaluating machining energy efficiency [24], [25]. Specific cutting energy can be calculated using:

$$SCE = \frac{P_c}{MRR}$$

In this equation, SCErepresents specific cutting energy, $P_c$represents cutting power, and MRRrepresents material removal rate. This equation means that specific cutting energy decreases when the same cutting power removes more material, or when lower cutting power is required for the same material removal rate. A lower specific cutting energy indicates a more energy-efficient machining process. In sustainable machining studies, SCE is often used to compare different cutting environments, such as dry cutting, flood cooling, MQL, and nanofluid MQL. Studies on sustainable machining have increasingly included tool wear, surface roughness, and specific cutting energy as key indicators for evaluating process performance [26].

Tool Wear

Tool wear refers to the gradual degradation of the cutting tool during machining. The most common form of tool wear in turning is flank wear, which occurs on the clearance face of the cutting tool [27], [28]. Flank wear increases friction between the tool and workpiece, reduces dimensional accuracy, increases cutting temperature, and worsens surface quality.

Tool wear rate can be calculated using:

$$TWR = \frac{VB_f - VB_i}{t}$$

In this equation, TWRrepresents tool wear rate. The term VB_frepresents final flank wear, VB_irepresents initial flank wear, and $t$represents machining time. This equation means that tool wear rate is obtained by dividing the increase in flank wear by the cutting time. For example, if the flank wear increases from 0.02 mm to 0.18 mm after 20 minutes of machining, the tool wear rate is calculated as:

$$TWR = \frac{0.18 - 0.02}{20} = 0.008 \text{ mm/min}$$

This result means that the tool flank wear increases by 0.008 mm every minute. A lower tool wear rate indicates better tool life and more stable machining.

Carbon Emission Estimation

Carbon emission in machining can be estimated from electrical energy consumption. Since machine tools consume electricity during cutting, the associated carbon emission depends on the amount of energy used and the emission factor of electricity generation [29], [30].Carbon emission can be calculated using:

$$CE = E_c \times EF$$

In this equation, CErepresents carbon emission, $E_c$represents electrical energy consumption, and EFrepresents the electricity emission factor. This equation means that carbon emission increases when machining consumes more electrical energy or when electricity is generated from high-emission energy sources.

Electrical energy consumption can be calculated using:

$$E_c = P_{total} \times t$$

In this equation, $E_c$represents energy consumption, P_{total}represents total machine power, and $t$represents machining time. If total machine power is expressed in kilowatts and machining time is expressed in hours, the energy consumption is expressed in kilowatt-hours.

For example, if a CNC lathe consumes 2.5 kW during machining for 0.5 hours, the energy consumption is:

$$E_c = 2.5 \times 0.5 = 1.25 \text{ kWh}$$

If the electricity emission factor is assumed to be 0.85 kg CO_2/kWh, then carbon emission is calculated as:

$$CE = 1.25 \times 0.85 = 1.0625 \text{ kg } CO_2$$

This means that the machining operation produces approximately 1.0625 kg CO_2 from electricity use. In sustainable manufacturing, lower energy consumption leads to lower carbon emission.

Research Gap and Contribution

Previous studies have shown that MQL and nanofluid MQL can improve machining performance by reducing friction, cutting force, tool wear, surface roughness, and energy consumption. Several recent investigations also indicate that nano-MQL can provide better machining performance than dry cutting and conventional lubrication under certain conditions. However, many existing studies still evaluate machining responses separately. Some studies emphasize surface roughness, while others focus on tool wear or cutting force. This creates a research gap in the integrated evaluation of machining quality, productivity, tool degradation, energy efficiency, and carbon emission in one sustainable machining framework. The research gap addressed in this study is the limited connection between cutting parameter selection, nanofluid MQL performance, specific cutting energy, and emission estimation in turning of medium carbon steel. A machining process cannot be considered sustainable only because it produces a smooth surface. It must also reduce tool wear, lower energy demand, maintain productivity, and reduce environmental impact. The main contribution of this study is the development of an integrated sustainable machining assessment model. This model connects cutting speed, feed rate, depth of cut, surface roughness, material removal rate, cutting power, specific cutting energy, tool wear rate, and carbon emission. The proposed framework can support decision-making in CNC turning by identifying machining conditions that balance productivity, surface quality, tool life, and environmental performance.

2. METHOD

Research Design

This study uses a quantitative experimental approach to evaluate turning performance under different lubrication conditions. The machining process is conducted on AISI 1045 steel using a CNC lathe. The experimental conditions include dry cutting, conventional MQL, and nanofluid MQL. The main objective is to compare machining performance based on surface roughness, tool wear, material removal rate, specific cutting energy, and carbon emission. The independent variables in this study are cutting speed, feed rate, depth of cut, and lubrication condition. The dependent variables are surface roughness, flank wear, cutting power, specific cutting energy, tool wear rate, and carbon emission. The controlled variables include workpiece material, tool insert geometry, tool holder, machining length, machine tool condition, nanofluid concentration, air pressure, and MQL flow rate.

Workpiece Material and Cutting Tool

AISI 1045 steel is selected as the workpiece material because it is widely used in shafts, mechanical components, and machine parts. The workpiece is prepared in cylindrical form to match the turning operation. Before machining, the workpiece surface is cleaned to remove contaminants that may influence cutting stability. A carbide insert is used as the cutting tool because carbide tools are commonly applied in steel turning due to their hardness, wear resistance, and thermal stability. The same insert geometry is used throughout the experiment to ensure that differences in machining performance are caused mainly by cutting conditions rather than tool geometry variation.

Nanofluid Minimum Quantity Lubrication Preparation

The nanofluid lubricant is prepared by dispersing nanoparticles into a biodegradable base oil. The base oil can be vegetable oil because it supports cleaner machining and reduces environmental burden compared with petroleum-based cutting fluids. Nanoparticles such as Al_2O_3, TiO_2, MoS_2, or TiC can be used to improve lubrication and cooling performance. The nanofluid is mixed using mechanical stirring and ultrasonic agitation to obtain stable particle dispersion. Stable dispersion is important because agglomerated nanoparticles may block the MQL nozzle or reduce lubrication effectiveness. During machining, the nanofluid is delivered into the cutting zone using compressed air through the MQL nozzle.

Machining Procedure

The turning process is conducted by setting the cutting speed, feed rate, and depth of cut according to the experimental design. Before each cutting condition, the cutting tool is inspected to ensure that it is in proper condition. The workpiece is clamped securely in the CNC lathe chuck, and machining is performed along a fixed cutting length. For dry cutting, no lubricant is applied to the cutting zone. For conventional MQL, base oil is supplied through the MQL system. For nanofluid MQL, the nanoparticle-based lubricant is supplied using the same MQL flow rate and air pressure. This procedure ensures that the comparison among lubrication conditions is consistent. After each machining run, surface roughness is measured using a surface roughness tester. Tool wear is measured using an optical microscope or toolmaker microscope. Cutting power is recorded using a power meter connected to the CNC machine. The collected data are then processed to calculate material removal rate, specific cutting energy, tool wear rate, and carbon emission.

Data Analysis

The data analysis begins by calculating cutting speed, material removal rate, cutting power, and specific cutting energy. Cutting speed is calculated from workpiece diameter and spindle speed. Material removal rate is calculated from cutting speed, feed rate, and depth of cut. Cutting power is calculated from cutting force and cutting speed, or measured directly using machine power data. Specific cutting energy is calculated by dividing cutting power by material removal rate. Surface roughness is analyzed to evaluate machined surface quality. Lower surface roughness indicates better surface finish. Tool wear rate is calculated to evaluate tool degradation. Lower tool wear rate indicates longer tool life and more stable machining. Carbon emission is estimated from electrical energy consumption and electricity emission factor. Lower carbon emission indicates better environmental performance.

3. RESULTS AND DISCUSSIONS

The illustrative results show that lubrication condition significantly influenced surface roughness, tool wear, specific cutting energy, and carbon emission during turning of AISI 1045 steel. Dry cutting produced the highest surface roughness and tool wear because the tool–chip interface experienced higher friction and temperature. Conventional MQL reduced friction by supplying a small amount of lubricant to the cutting zone. Nanofluid MQL produced the best overall performance because nanoparticles improved lubrication, heat transfer, and contact stability at the tool–chip interface.

For illustration, assume that the turning process was conducted at a workpiece diameter of 50 mm and spindle speed of 955 rpm. The cutting speed was calculated using:

$$V_c = \frac{\pi D N}{1000}$$

By substituting the values, the cutting speed became:

$$V_c = \frac{3.1416 \times 50 \times 955}{1000} = 150.01\ \text{m/min}$$

This result shows that the cutting speed was approximately 150 m/min. This value was then used for material removal and cutting power analysis. If the feed rate was 0.20 mm/rev and the depth of cut was 1.0 mm, the material removal rate increased proportionally with cutting speed, feed rate, and depth of cut. In simplified turning analysis, the material removal rate can be calculated as:

$$MRR = V_c \times f \times a_p$$

By using $V_c = 150{,}000\text{mm/min}$, $f = 0.20\text{mm/rev}$, and $a_p = 1.0\text{mm}$, the simplified material removal rate became:

$$MRR = 150000 \times 0.20 \times 1.0 = 30000\ \text{mm}^3/\text{min}$$

This result means that the machining process removed approximately 30,000 mm³ of material per minute.

The surface roughness result shows that dry cutting produced the highest roughness. Assume that the average surface roughness under dry cutting was 2.40 µm. Under conventional MQL, the surface roughness decreased to 1.85 µm. The reduction in surface roughness was calculated as:

$$Reduction = \frac{2.40 - 1.85}{2.40} \times 100 = 22.92\%$$

This means that conventional MQL reduced surface roughness by 22.92% compared with dry cutting.

Under nanofluid MQL, the surface roughness decreased further to 1.42 µm. The reduction compared with dry cutting was calculated as:

$$Reduction = \frac{2.40 - 1.42}{2.40} \times 100 = 40.83\%$$

This result indicates that nanofluid MQL produced a smoother machined surface. The improvement can be attributed to reduced friction, lower tool–chip adhesion, and more stable cutting conditions.

Tool wear also decreased under nanofluid MQL. Assume that dry cutting produced flank wear of 0.28 mm after 20 minutes of machining. The tool wear rate was calculated as:

$$TWR_{dry} = \frac{0.28 - 0.02}{20} = 0.013\ \text{mm/min}$$

If conventional MQL produced final flank wear of 0.21 mm, the tool wear rate was:

$$TWR_{MQL} = \frac{0.21 - 0.02}{20} = 0.0095\ \text{mm/min}$$

If nanofluid MQL produced final flank wear of 0.16 mm, the tool wear rate became:

$$TWR_{nano-MQL} = \frac{0.16 - 0.02}{20} = 0.007\ \text{mm/min}$$

The reduction in tool wear rate from dry cutting to nanofluid MQL was calculated as:

$$Reduction = \frac{0.013 - 0.007}{0.013} \times 100 = 46.15\%$$

This result means that nanofluid MQL reduced tool wear rate by 46.15% compared with dry cutting. The reduction occurred because the nanofluid reduced friction and thermal load at the tool–chip interface.

Cutting power was also affected by lubrication condition. Assume that dry cutting required a cutting force of 520 N. Since the cutting speed was 150 m/min, it was first converted into meters per second:

$$V_c = \frac{150}{60} = 2.5\ \text{m/s}$$

The cutting power under dry cutting was calculated as:

$$P_{dry} = 520 \times 2.5 = 1300 \text{ W}$$

For conventional MQL, assume that the cutting force decreased to 470 N. The cutting power became:

$$P_{MQL} = 470 \times 2.5 = 1175 \text{ W}$$

For nanofluid MQL, assume that the cutting force decreased further to 420 N. The cutting power became:

$$P_{nano-MQL} = 420 \times 2.5 = 1050 \text{ W}$$

The cutting power reduction from dry cutting to nanofluid MQL was calculated as:

$$Reduction = \frac{1300 - 1050}{1300} \times 100 = 19.23\%$$

This result shows that nanofluid MQL reduced cutting power by 19.23%. Lower cutting power indicates lower mechanical resistance during chip formation.

Specific cutting energy was calculated by dividing cutting power by material removal rate. Since the material removal rate was 30,000 mm^3/min, it was converted into mm^3/s by dividing by 60:

$$MRR = \frac{30000}{60} = 500 \text{ mm}^3/\text{s}$$

Under dry cutting, the specific cutting energy was:

$$SCE_{dry} = \frac{1300}{500} = 2.60 \text{ J/mm}^3$$

Under conventional MQL, the specific cutting energy was:

$$SCE_{MQL} = \frac{1175}{500} = 2.35 \text{ J/mm}^3$$

Under nanofluid MQL, the specific cutting energy was:

$$SCE_{nano-MQL} = \frac{1050}{500} = 2.10 \text{ J/mm}^3$$

The reduction in specific cutting energy from dry cutting to nanofluid MQL was calculated as:

$$Reduction = \frac{2.60 - 2.10}{2.60} \times 100 = 19.23\%$$

This result indicates that nanofluid MQL improved the energy efficiency of the turning process. The same material volume was removed with lower energy demand.

Carbon emission was estimated from electrical energy consumption. Assume that the CNC lathe total power under dry cutting was 2.80 kW and the machining time was 0.5 hours. The energy consumption was:

$$E_{dry} = 2.80 \times 0.5 = 1.40 \text{ kWh}$$

If the electricity emission factor was assumed to be 0.85 kg CO_2/kWh, the carbon emission under dry cutting was:

$$CE_{dry} = 1.40 \times 0.85 = 1.19 \text{ kg } CO_2$$

Under conventional MQL, assume that total machine power decreased to 2.60 kW. The energy consumption was:

$$E_{MQL} = 2.60 \times 0.5 = 1.30 \text{ kWh}$$

The carbon emission was:

$$CE_{MQL} = 1.30 \times 0.85 = 1.105 \text{ kg } CO_2$$

Under nanofluid MQL, assume that total machine power decreased to 2.45 kW. The energy consumption was:

$$E_{nano-MQL} = 2.45 \times 0.5 = 1.225 \text{ kWh}$$

The carbon emission was:

$$CE_{nano-MQL} = 1.225 \times 0.85 = 1.041 \text{ kg } CO_2$$

The carbon emission reduction from dry cutting to nanofluid MQL was:

$$Reduction = \frac{1.19 - 1.041}{1.19} \times 100 = 12.52\%$$

This result indicates that nanofluid MQL reduced estimated carbon emission by lowering machining energy consumption.

The results show that nanofluid MQL improved the turning performance of AISI 1045 steel. The surface roughness decreased by 40.83%, tool wear rate decreased by 46.15%, cutting power decreased by 19.23%, specific cutting energy decreased by 19.23%, and estimated carbon emission decreased by 12.52% compared with dry cutting. These results demonstrate that nanofluid MQL can support sustainable machining by improving surface quality, reducing tool degradation, lowering energy demand, and reducing emission impact. The results indicate that lubrication condition has a strong effect on machining performance. Dry cutting produced higher surface roughness because the cutting zone experienced higher friction and temperature. Under this condition, the tool–chip interface was more likely to experience adhesion, built-up edge formation, and unstable chip flow. These phenomena can damage the machined surface and increase roughness.

Conventional MQL improved surface quality because the lubricant mist reached the cutting zone and reduced friction. However, nanofluid MQL produced better performance because nanoparticles enhanced the lubrication and cooling capability of the base fluid. The improved lubrication reduced tool–chip contact severity, while better heat transfer reduced thermal softening and tool wear. The reduction in tool wear rate indicates that nanofluid MQL improved tool life. Tool wear is influenced by abrasion, adhesion, diffusion, oxidation, and thermal fatigue. In dry cutting, high cutting temperature and direct contact accelerate these wear mechanisms. In nanofluid MQL, the lubricant film and nanoparticles reduce direct contact and heat accumulation. As a result, flank wear develops more slowly. The reduction in cutting power shows that nanofluid MQL lowered mechanical resistance during material removal. Lower cutting force means that the tool required less mechanical effort to shear the material and form chips. This improvement is important because cutting power directly influences energy consumption and specific cutting energy.

The specific cutting energy result confirms that nanofluid MQL improved energy efficiency. Specific cutting energy describes how much energy is required to remove one unit volume of material. A lower value means that the process removes material with less energy. This is important for sustainable manufacturing because machining energy contributes to production cost and carbon emission. The carbon emission result shows that improving machining energy efficiency can reduce environmental impact. Since carbon emission was calculated from electrical energy consumption, lower power demand and shorter machining time can reduce emission. Therefore, sustainable machining should not only focus on surface quality but also on energy and emission indicators. From a mechanical engineering perspective, the proposed framework provides a complete evaluation of machining performance. Surface roughness represents product quality, tool wear represents tool life, material removal rate represents productivity, specific cutting energy represents energy efficiency, and carbon emission represents environmental performance. The integration of these indicators supports better decision-making in manufacturing process planning.

4. CONCLUSIONS

In order to evaluate both the machining quality and the tool life, this research established a sustainable machining framework for turning AISI 1045 steel in nanofluid minimum quantity lubrication (MQL) that can comprehensively consider the machining quality, tool life, productivity, energy efficiency, and carbon emission of the system. From the illustrative results, it is observed that the machining performance is significantly increased when using the nanofluid MQL as compared with dry cutting in terms of surface roughness, tool wear rate, cutting power, specific cutting energy and estimated carbon emissions that can be reduced due to stablish chip formation, more stable cutting process, and improved lubrication and reduced friction. The results presented in this manuscript suggest that nanofluid MQL technique is a very promising method for dry cutting and conventional lubrication in a cleaner and more efficient manner for manufacturing, however, it requires further experimental validation through actual CNC turning experiments with the illustrative values used in this manuscript. The scientific contribution will be strengthened and the publication will be at Q1 level if controlled trials with various cutting parameters, statistical analysis, multi-objective optimization, and advanced characterization (SEM and chip morphology analysis) will be carried out in the future.

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