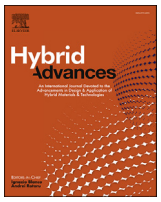
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Comparative life cycle analysis of environmental and machining performance under sustainable lubrication techniques



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ABSTRACT

One of the issues confronting manufacturers is the requirement for establishing sustainable production methods, which poise between economic feasibility and ecological preservation. Alternative sustainable cutting fluid methods must be developed since the traditional lubricants employed in machining operations are unsustainable from the environmental impact point of view. The balance between energy-production demand and quality-productivity is required for sustainable production. In this respect, this research studies the tool life, machining efficiency, energy consumption, and carbon emission under dry, flood machining, and minimum quantity lubrication machining. This study comprises two parts: evaluation of machining characteristics in terms of tool life, machining efficiency, energy consumption, and carbon emission, and the life cycle assessment (LCA) of inventories used during machining experimentation. The outcomes of this novel work revealed an increase of 42% and 61% in tool life at a cutting speed of 185 m/min under flood and MQL media than dry machining. At a cutting speed of 185 m/min in three different lubricating conditions, the percentage increase in the efficiency was 31%, and 28% for dry, flood, and MQL machining. In MQL machining, due to more uniform lubrication than flood machining, energy usage decreases by 38%, 32%, and 27% at the rate of metal removal of 93.67, 131.68, and 152.36 mm^3/min. Also, A decrease in CO_2 emissions of 16%, 21%, and 18% was attained in MQL machining than flood machining at 185, 215, and 245m/min cutting speeds. Furthermore, this also compares life cycle inventory analysis in dry, flood, and minimum quantity lubrication. Gate-to-gate approach methodology adopted for LCA analysis of system boundaries and functional unit to examine the environmental impression through ReCipe 2016, Endpoint (H) methodology. Sustainable assessment through life cycle analysis determined that dry and mist machining are more sustainable than wet machining.

1. Introduction

Global warming is caused by difficulties with resource management and environmental pollutants. Carbon dioxide, methane, nitrous oxide, and other gas contaminants are all classified as greenhouse gases and are quantified in CO_2 equivalents. There is a considerable amount of work being done and will be done on carbon neutrality, which is something that the research community is aiming for [1]. Many manufacturing companies collaborate to create rules for producing high-quality products with low industrial waste and optimal raw material consumption. A sustainable approach is proposed by life cycle assessment, which includes three main characteristics of environmental, economic, and social impact indicators. Sustainable manufacturing is vital to creating goods that benefit the economy, society, and environment. Critical aspects of product environmental sustainability include energy consumption, material waste, various sorts of emissions, and a reduction in the use of non-renewable resources [2]. Any organization's growth is primarily driven by its manufacturing performance. The sustainability concept, which strives to integrate supply chain management systems with economic, environmental, and social factors, has significantly influenced any country's development. Given that the manufacturing sector in India contributes between 14 and 18% of the country's GDP, it is crucial to consider its expansion.

LCAs have been conducted on the unit level for various manufacturing systems, primarily for milling [3], turning [4], and grinding [5]. However, relying on LCA to support sustainable and green manufacturing methods may be insufficient. Cleaner production will only be possible with engineering concepts and the design of experiments. LCA analyses stages of material extraction-end life phase and their system for sustainable production by environmental impact analysis [6,7].

Two important methods to increase a product's competitiveness are to lower production costs and raise product quality. Due to the high level of friction during dry machining, the tool will overheat. It produces much

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Abbreviations

MQL	Minimum quantity lubrication
LCA	Life cycle assessment
FU	Functional unit
WCAE	Water consumption, Aquatic ecosystems
GWFE	Global warming, Freshwater ecosystems
MEPH	Marine eutrophication
TET	Terrestrial ecotoxicity
MEET	Marine ecotoxicity
WCTE	Water consumption, Terrestrial ecosystem
FET	Freshwater ecotoxicity
SOD	Stratospheric ozone depletion
LU	Land use
IR	Ionizing radiation
FEP	Freshwater eutrophication
OFTE	Ozone formation, Terrestrial ecosystems
TAD	Terrestrial acidification
OFHH	Ozone formation, Human health
GWTE	Global warming, Terrestrial ecosystems
WCHH	Water consumption, Human health
HNCI	Human non-carcinogenic toxicity
HCCT	Human carcinogenic toxicity
GWHH	Global warming, Human health
FPMF	Fine particulate matter formation
MRS	Mineral resource scarcity
FRS	Fossil resource scarcity

heat, which causes more significant tool wear, shorter tool life, and difficulties with chip production. Due to these reasons, dry machining has become challenging in several machining methods. Such tools can nevertheless be protected from deterioration by coolants. Cutting fluids are commonly used to cool the cutting tool and lubricate the machining process [8].

On the other hand, cutting fluids is expensive and negatively impacts the environment. Although it appears to be a reasonable explanation for high temperatures, it postures a spartan health hazard and jeopardizes enduring sustainable growth [9,10]. Flood lubrication or dry cutting are alternatives to MQL that are both economical and environmentally benign. It uses an acceptable smog of trodden air and lubricant flowing at a rate of 15–300 ml/h and a pressure of around 6–10 bar. Less cutting fluid is used, less damage is done to the environment, expenses are cheaper, and overall machining accuracy and surface finish are more special thanks to MQL [11].

2. Machining sustainability

Machining processes are the main components in the production industry and contribute a lot to the growth of the global economy. Machining performance increases with improved tool-workpiece materials, and eco-friendly environment techniques are becoming extremely popular for cleaner production. The temperature generated during machining will not be the same for some materials such as stainless steels, superalloy, Inconel, Titanium grades, etc. It can be reduced with the use of cutting fluids but have a direct impact on the environment and cost. Certain cutting fluids are carcinogenic and expose the operator to various skin diseases, cancer, etc. Thus, using sustainable lubrication (dry machining, MQL, cryogenic machining, etc.) in manufacturing becomes an obvious choice. For sustainable analysis, LCA is useful for assessing the environmental impact and comparing different cooling strategies [12]. investigated the impact on the environment concerning surface roughness and power generated during the machining of AISI 1045 steel. The sustainable assessment is also carried out for machining cost, waste management, and the worker's health. Results showed a 23% increase in sustainability index during nanofluid minimum quantity lubrication. Better performance is less resource utilization, low lubricant usage, and less energy consumption.

Dry machining gives the best results in sustainability indicators due to the absence of lubricant and no requirement for power to run the air compressor. Thus, in all three lubricating conditions, dry machining is the most sustainable process as it gives an increase of 35% in the sustainable index [13]. conducted a similar investigation in the machining of titanium alloy with surface quality, power consumption, and flank wear as output parameters under MQL and nano-MQL environments. A specially designed algorithm is used for the estimation of design variables. The study's sustainable indicators were the worker's safety, environmental impact, and waste management. LCA results revealed that machining trials performed under nano-fluid lubrication [14] give better results in less power consumption, tool wear, and fewer fumes inhalation by the operator.

LCA is a handy tool for environmental impact assessment during each product's life-cycle for sustainability. It is widely applied in various machining operations involving the use of lubricants [15]. compared the LCA results of water and air-based delivery of lubricants. Air lubricant proved more effective in aquatic toxicity and solid waste and reducing the health concerns of the operator. From the cooling and lubrication perspective, air-delivered lubrication is not adequate; for these machining operations, supercritical CO_2 -based lubrication gives promising results in cooling and ecological advantage. Moreover, it was concluded that gas-based lubricant is more promising toward global warming potential than water-based lubricant [7]. investigated the resource utilization in flood and MQL lubrication strategies during milling and turning on steel, cast iron, and aluminium. By hotspot analysis derived from the CML baseline 2001 method, electricity, lubricant, and compressed air are responsible for environmental impact. Due to less lubricant consumption in the MQL strategy, water toxicity is comparatively lower than flood lubrication. However, compressed air usage in MQL is significantly higher than flood lubrication.

[16] investigated climate change using the ReciPe method on seventeen impact categories in electric-discharge machining of medium carbon steel. Inventory data was collected on electricity consumption, lubricating oil, coolant usage time, and chip disposal. They analyzed that carbon dioxide emission is more prominent toward global warming [9]. compared environmental footprints and carcinological and non-carcinological impact on operator health with wet machining, minimum quantity lubrication, cryogenic cooling, mixed cryogenic, CO_2, LN_2, and dry machining. As mineral-based oils produce more harmful fumes during machining, thus the inhalation capacity increases in all coolant conditions. But in dry machining conditions, heat dissipation is minimal and increases the temperature of whole working areas. That is why dry machining increases the impact of non-carcinogenicity. Due to the absence of lubricating oils, Co_2 gives the best 19% decrease in non-carcinogenic impact compared to dry machining.

[17] compared the dry, flood, and MQL lubrication during milling of alloy steel with the Eco-indicator 99(H) LCA method. The preparation of material and scrap management are also considered in the analysis, along with the material removal rate. Results revealed that flood machining has a higher environmental impact than dry and MQL machining [18]. drawn a comparison by life cycle analysis on machine usage in additive manufacturing and CNC machining. LCA results governed by the ReciPe endpoint (H) method revealed that CNC machining is less sustainable than additive manufacturing (AM) due to more waste production.

[19] performed laser-assisted machining on titanium alloy, steel 304, Inconel 625, and alumina with kerf width as a process parameter. LCA is

employed to assess the environmental effect of material wastes. Results revealed that material selection in laser machining is vital for environmental safety. Among all, Inconel 625 has environmental damage. However, its contribution can be reduced significantly by recycling the waste [20]. Gate-to Gate life cycle analysis in different cooling conditions (near dry, flood, and cryogenic) was performed by considering coolant consumption, land utilization, and water usage as sustainability indicators. The functional unit (FU) is selected as 1 kg of material removal and performed on SimaPro 8.0.1 software with Eco-indicator 99. Results interpreted that flood machining contributes more toward human health and resources. Moreover, MQL machining has more impact on the ecosystem than cryogenic machining.

[21] conducted turning of alloy steel under various lubricating mediums, considering machining forces and surface roughness as process parameters. The functional unit utilizing emulsion was selected through the cradle-to-gate approach for life cycle analysis. Results showed that jatropha emulsion is a sustainable substitute for metalworking fluids and has less environmental impact [6]. performed machining trials on Ti–6Al–4V under dry and liquid nitrogen lubrication. Life cycle analysis was carried out by EPS 2000 method, and inventory data was collected from the experimentation. Results presented a relationship between lubricating strategy and environmental indicators such as biodiversity and human health. Liquid nitrogen cooling improves the machining quality in comparison with dry machining [22]. conducted life cycle analysis using the ReCiPe 2016 midpoint (H) method during Inconel 718 drilling in cryogenic, carbon dioxide & LN_2 lubricating medium. LCO_2 gives higher machining performance by less cutting temperature generation and low power consumption. Furthermore, the ecological effects are better than LN_2 machining.

This study assesses the internal turning operation on aluminium alloy 6061 in three machining conditions and compares the machining performance in terms of tool life, energy demand, and CO_2 emissions. Moreover, the gate-to-gate approach performs a life cycle assessment [12] based on data acquisition from experimental inventory. And to conclude, which lubricating strategy is more resource efficient and sustainable in terms of ecological indicators.

3. Material and methods

Internal turning trials were executed on 200-mm long aluminum alloy 6061 with carbide insert Kennametal through-hole boring bar on a conventional lathe at different cutting parameters. The in-house fabricated set-up has been used to carry out the experimental work. A specially designed mist nozzle with a mixing chamber is utilized, and the output is taken through the boring bar to lubricate the tool-workpiece interface. A single line with a mixing chamber is created by grooving a slot, and a 120-mm long nozzle having a diameter of 8.8 mm is used for MQL supply for the experimentation. Include spray angle kept at 60° to maintain the coverage distance of approximately 58 mm. Experiments were conducted under dry, flood, and MQL media to evaluate the extensive machinability features. Water miscible cutting fluid is used for flood and mist lubrication which is commercially available. It offers substantial lubrication and cleaning of the machined surface and is also less toxic in nature than conventional coolants [23].

Specimens for boring operations were prepared from commercially available aluminium alloy 6061 extruded pipe. The length of the workpiece was 457 mm, the internal diameter was 69mm, and it was 3 mm in thickness (Fig. 1), (Table 1), and (Table 2) showcased the chemical compositions and properties of the material as per ASTM standards. Silicon and magnesium are chief alloying elements that give resistance to high temperatures and maintain substantial strength during machining.

Aluminium alloy 6061 has good machinability due to work hardening and good thermal conductivity. It is corrosion-resistant and widely used for various industrial applications. The x-ray diffraction (XRD) analysis reflects the composing elements of the material (Fig. 2). The diffraction pattern indicated the presence of elements in the alloying form in various



Fig. 1. Specimens for machining.

peaks. The XRD patterns of Al0.99Cu0.01 and (Fe19Si)0.1are much similar except for peak intensity and shape. These changes appear due to silicon and magnesium in high peaks. Smaller peaks correspond to other elements like zinc, nickel, iron, etc.

(Fig. 3) represent the EDS analysis of aluminium alloy 6061 without machining. The spectrum represents the composing elements, and their weight percentages are given in Table 3. Aluminium, magnesium, zinc, and manganese are the chief elements, and the rest of the materials are in small proportions, as depicted in (Fig. 4).

A constant cutting length of 80 mm was used for all machining trials. The boring bar was employed with an overhang length of 260 mm. From the detailed literature survey, cutting speed, feed rate, and lubrication medium was selected as input parameters. Taguchi L_{27} orthogonal array was selected for experimental cutting conditions and lubricating medium combinations. Three input factors, such as cutting speed, feed rate, and lubrication medium, are used to evaluate the effect on output parameters [25–27]. The factors and their levels are given in Table 4. The selected orthogonal array is shown in Table 5. For evaluation of the machining productivity, three different machining mediums were selected: (i) dry machining, (ii) flood machining, and (iii) minimum quantity lubrication machining. Flood machining is achieved via water-miscible cutting fluids supplied by a through-hole boring bar. The cutting fluid flow rate was kept constant at 12,000 ml/h. MQL machining was performed with an in-house fabricated mist nozzle connected with a boring bar. The mist supply was at 100 ml/h, and a pressure of 6 bar was provided through an air compressor. The main reason for the mist selection is to achieve better penetration [28] of cutting fluids in the machining areas and the chip zone. The experimental conditions (Table 6) and set-up is given in (Fig. 5).

4. Results and discussion-machining performance

The machining results procured from the experimentation under dry, flood and MQL lubrication environments are given in Table 7. The resources utilization for the machining trials are further utilized as ecoloogical assessment, which compares the three cutting medium on sustaiable indicators like global warming and air contamination.

4.1. Tool life

Coolant usage gives better tool life in machining various grades of materials [29]. It was calculated by measuring flank wear at the cutting tip after successive experimental runs. Tool life (Fig. 6) decreases when the cutting speed increases from 185m/min to 245m/min. It is due to increased machining temperature at high cutting speed, resulting in decreased tool life. At a cutting speed of 185 m/min, tool life increases by 42 and 61% in flood and MQL machining than in dry machining. It's because of the rapid dispersion of lubricant particles across the cutting zone due to cutting fluid impingement and the presence of mist film by pressurized gas. Due to this, tool wear decreases across the rake face and

Table 1
Chemical compositions of aluminium alloy 6061 [24].

Element	Mg	Si	Fe	Cu	Cr	Zn	Ti	Mn	Al
Amount (wt%)	0.8–1.2	0.4–0.8	0.7	0.15–0.4	0.04–0.035	0.25	0.15	0.15	96.85

Table 2
Properties of aluminium alloy 6061.

Properties	Value
Hardness (BHN)	95
Ultimate tensile strength (MPa)	310
Yield strength (MPa)	277
Machinability	50%
Elongation	13%
Modulus of elasticity (GPa)	69
Thermal conductivity (W/m-K)	168

felicitates easy chip disposal across the rake face.

The highest tool life was obtained at 185 m/min cutting speed in MQL condition, followed by flood and dry machining. A similar trend was observed at 215 and 245 m/min cutting speeds, irrespective of cutting medium. This trend is similar to the results obtained by Refs. [30,31] to evaluate tool wear occurrence and tool life evaluation. Marques et al. achieved a 21% enhancement in tool life using Molybdenum disulfide solid lubricant in MQL cutting medium compared to graphite. It is due to the formation of Vander walls forces which allows slipping from each other.

4.2. Machining efficiency

Determination of optimal cutting conditions plays a vital role in getting maximum output from a machine tool. During the machining trials, Cutting time (sec), stand-by time (sec), and tool return time (sec) were recorded. The sum of all such times comprises the total machining time [32]. Thus, a forward feed of 0.15mm/rev is used for actual machining, while 2.5mm/rev in air cutting. For single component production, the machining efficiency is derived from equation (1) [33]:

$$\eta = \frac{T_{cutting}}{T_{machine}} * 100 \quad (1)$$

$T_{cutting}$ is the actual cutting time, and $T_{machine}$ is the total machining time (Fig. 7). clearly shows that machining efficiency decreases when the cutting speed increases. At a cutting speed of 185m/min in three different lubricating conditions, the percentage increase in the efficiency was 31%, and 28% for dry, flood, and MQL machining. At 215 and 245 m/min, ŋ increases significantly due to flood and mist lubricants. Notably, increased tool life accounts for an increment in machining efficiency due to thick film generation between the tool and the workpiece. It decreases machining temperature and shear stress accumulation in the machining zone. Overall, the maximum efficiency reported in MQL media, even at a higher cutting speed than dry and flood machining. These results can be correlated with [33], where Gupta et al. presented an improvement of 2.4%, 7%, and 9% in near-dry machining, nanofluid MQL, and N_2 machining than dry machining. From the experimentation and (Fig. 7), it is proved that ŋ decreases with increased speed. Thus it further increases flank wear, surface roughness, machining temperature, and consequently, the tool's life. Due to this, tool replacement time rises and improves the overall production time, dramatically affecting the unit production cost.

4.3. Energy consumption

Machining energy consumption accounts for a large portion of production costs and has a considerable environmental impact. Energy usage is identified at the method, equipment, and set-up levels [34]. A machining process's energy usage may be examined at three tiers: machine tool, spindle, and operation. At the machine level, the energy

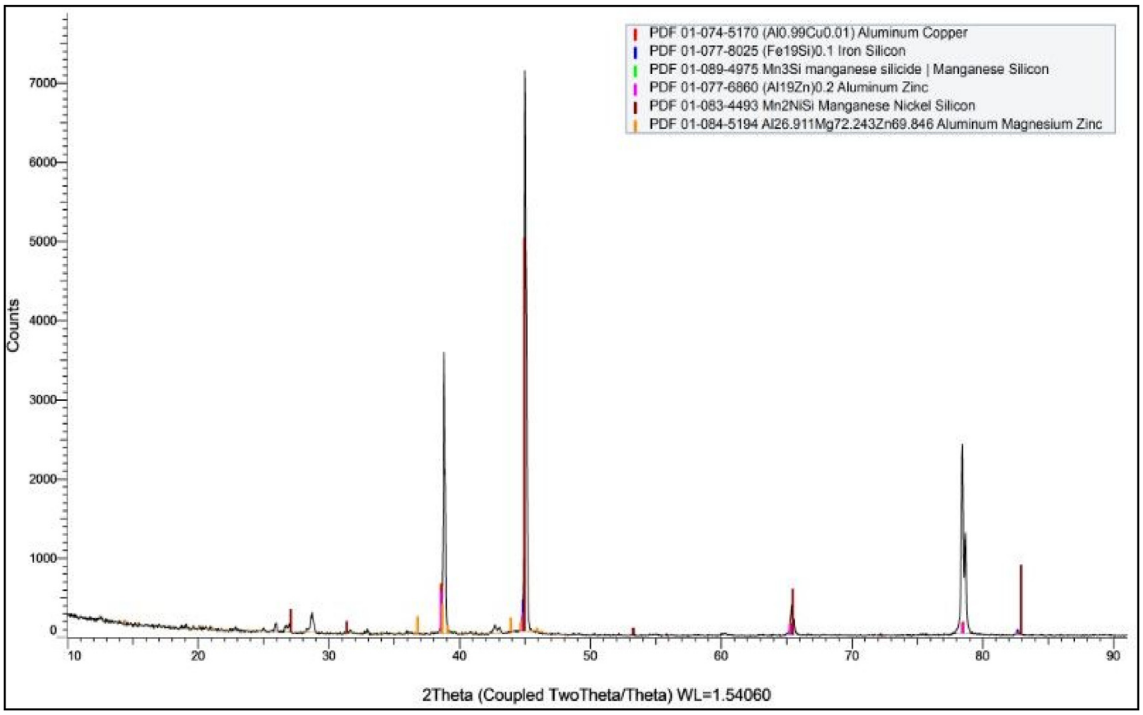


Fig. 2. XRD analysis of the material.

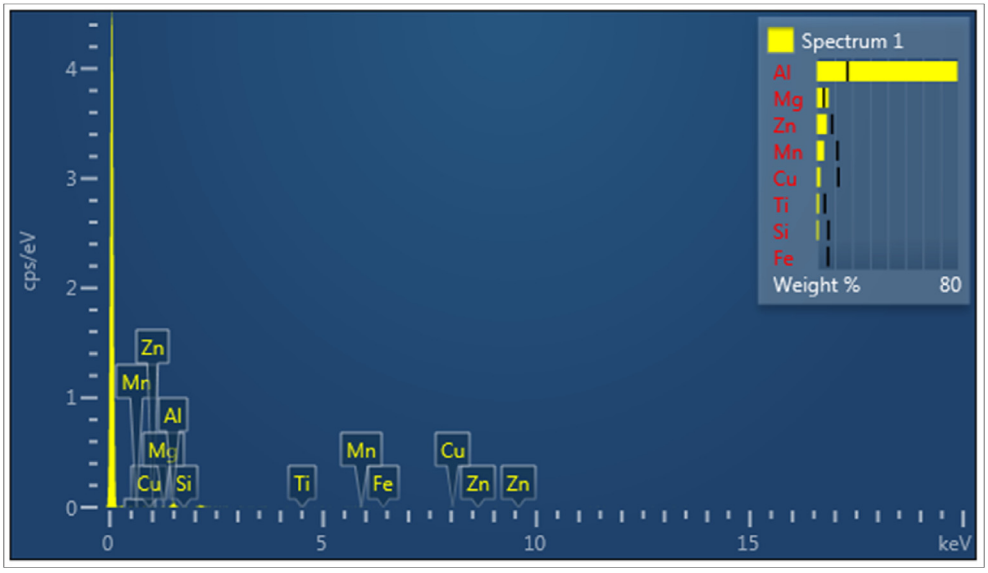


Fig. 3. Energy dispersive spectroscopy (EDS) spectrum of the material.

Table 3
Diffraction pattern of alloying elements.

Spectrum 1	Wt%	Wt% Sigma	Spectrum 1	Atomic %
Zn	5.60	8.65	Zn	2.47
Cu	1.91	12.27	Cu	0.87
Fe	0.00	6.35	Fe	0.00
Mn	4.05	11.62	Mn	2.12
Ti	1.20	4.49	Ti	0.72
Si	1.01	6.58	Si	1.04
Al	79.63	17.30	Al	84.97
Mg	6.60	3.91	Mg	7.82
Total	100.00		Total	100.00

required by the complete machine tool (e.g., control mechanisms, cooling and lubrication units, drive systems, spindle motor, and manufacturing process) is analyzed. Investigating the relationships between power usage and machining parameters at this stage is advantageous for enhancing the total effectiveness of machine equipment. At the component level, only the power necessary for actual material removal is included, regardless of the machine tool. Chip formation and surface creation are governed by energy demand at the process level. As a result, while setting process variables to balance energy consumption with surface integrity, this power should be considered [35].

In this novel work, energy usage was calculated by taking idle energy, tool replacement energy, machining energy, and aircut energy as given in equation (2) [36]:

$$E_T = E_i + E_{tr} + E_{me} + E_{ac} \tag{2}$$

E_T is total energy consumption, E_i is idle energy consumption, E_{tr} is energy usage in tool replacement, E_{me} is machining energy consumption, and E_{ac} is air cutting energy usage. From (Fig. 8), it is understood that energy usage increases with an increase in material removal rate. It is due to the increased depth of cut utilized for machining and more power requirement to run the spindle and motors at higher cutting speeds. Higher cutting speed also increases tool wear, and more energy is required for tool replacement. The highest energy demand arises in dry machining as the machining is to be performed without cutting fluids. More heat generation also deteriorates the surface finish of the finished component due to increased machining temperature. On a similar note, in flood machining, energy consumption increases with an increase in material removal rate but is comparatively lower than in dry machining.

Flood machining decreases energy usage at a material removal rate of 93.67, 131.68, and 152.36 mm^3/min and by 14%, 7%, and 35% due to cutting fluids, which reduces the cutting temperature and also increases the tool life. In MQL machining, due to more uniform lubrication than flood machining, energy usage decreases by 38%, 32%, and 27% at the rate of metal removal of 93.67, 131.68, and 152.36 mm^3/min. Thus, it is evident that MQL machining gives the best results in energy consumption than dry and flood machining. These results are validated by similar research by Makhesana and Patel on MQL-assisted Inconel machining. They significantly reduced about 48% and 63% of energy demand with solid lubrication near dry machining and near dry machining [37].

4.4. Comparison of carbon emissions in different cutting conditions

Environmental aspects, cost, and production efficiency drive the decision of sustainable machining. Carbon emissions are considered for dry, flood, and MQL machining, wherein dry machining consumes more power without the lubricant; high-speed machining is the only option for more material removal. Material removal increases in wet and MQL environments, but the carbon generation may increase during lubricant disposal. For various machining processes such as turning, drilling, and milling operation [38–40], carbon generation creates ecological imbalances and global warming. This novel work focuses on reducing carbon emissions by various machining conditions. Generally, energy usage increases carbon generation in a machining process [41]. The total emission of carbon in internal turning operation is derived from equation (3) [42].

$$C_{et} = C_{el} + C_{et} + C_{cl} \tag{3}$$

C_{et} represents total carbon emissions, C_{el} – electrical energy consumption, C_{et} – carbon emissions through the tool, and C_{cl} – lubricants carbon emissions. Total carbon emissions are expressed from carbon dioxide release. From (Fig. 9), it can be understood that cutting under dry conditions increases energy consumption due to an uplift in thermal stress across the deformation zone, which enhances cutting temperature. That is why more energy is used to machine a component, leading to more carbon emissions at higher speed values [43]. During dry machining, when the cutting speed increases from 185 to 245 m/min, a considerable increase in carbon emissions (Kg-CO_2) of 13%, 19%, and 21% was observed.

Conversely, a decreasing trend of carbon emissions was obtained in flood machining. A vital decrease of 14%, 24%, and 26% in total CO_2

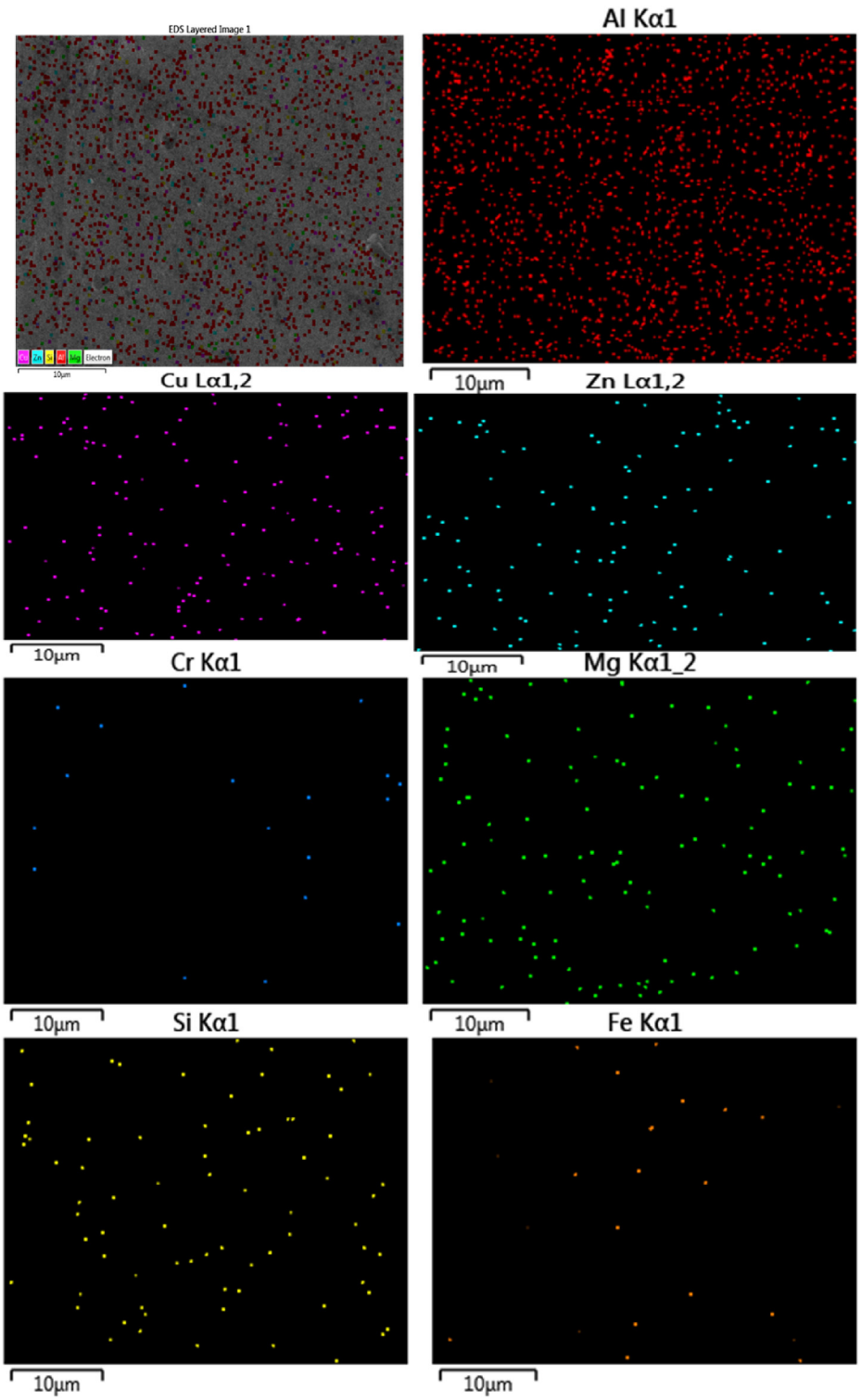


Fig. 4. EDS spectrum distribution of alloying elements.

Table 4
Machining limits with different settings.

Limits	Symbol	Units	Settings		
			1	2	3
Cutting speed (A)	V_c	m/min	185	215	245
Feed rate (B)	f_r	mm/rev	0.15	0.20	0.25
Depth of cut (C)	w	mm	0.3	0.5	0.7
Coolant medium (D)	C_m	–	Dry	Flood	MQL

emissions was attained at 185, 215, and 245 m/min cutting speeds. It is due to the decreased cutting temperature obtained through the thick film between the machining areas and the cutting tool. It decreases the power required to run the spindle and other reciprocating parts in a machine tool, ultimately reducing the power consumption.

Like flood cooling results, MQL gives the best possible energy consumption and carbon dioxide emission reduction. The mist serves the purpose of cooling and lubrication due to smoggy actions; it also reduces the coolant losses. Machining temperature and the energy consumption is

Table 5
Taguchi experimental design L_{27} orthogonal array.

Trial number	Controllable input parameters			
	A	B	C	D
1	1	1	1	1
2	1	1	1	1
3	1	1	1	1
4	1	2	2	2
5	1	2	2	2
6	1	2	2	2
7	1	3	3	3
8	1	3	3	3
9	1	3	3	3
10	2	1	2	3
11	2	1	2	3
12	2	1	2	3
13	2	2	3	1
14	2	2	3	1
15	2	2	3	1
16	2	3	1	2
17	2	3	1	2
18	2	3	1	2
19	3	1	3	2
20	3	1	3	2
21	3	1	3	2
22	3	2	1	3
23	3	2	1	3
24	3	2	1	3
25	3	3	2	1
26	3	3	2	1
27	3	3	2	1

Table 6
Experimental conditions.

Machine Tool	Conventional Lathe Machine
Work material	Aluminium alloy 6061
Dimensions	Ø69 and 3 mm thickness
Boring Bar Specifications	Kennametal A16T-SVUBR3NH2, Ø30 mm, l: 305, l/d ratio:10 mm
Cutting insert geometry	VNMG160408-QM wintechcarbide, L:16.6 mm, D: 9.525, S: 4.76, d_1: 3.81, R: 0.8, Positive rake
Process parameters	v_c: 185, 215, 245 m/min, f_n: 0.15,0.20,0.25 mm/rev, a_p: 0.3,0.5,0.7 mm
Cutting Condition	Dry, Flood and MQL
Air Pressure & Lubricant Flow rate	6 bar, Dry: 0 ml/h, Flood: 120,000 ml/h, MQL: 100 ml/h though internal nozzle in boring bar
Cutting Fluid	M70 water miscible cutting fluid (commercially available)

far temperature than dry and flood machining, even at higher cutting speeds. A decrease in CO_2 emissions of 16%, 21%, and 18% was attained in MQL machining than flood machining. While comparison with dry machining, an overall reduction in CO_2 emissions was close to 44%. These findings correlate well with a similar work done by Gupta et al. during Inconel 800 machining, where a similar comparison between dry, flood, MQL, and N_2 concerning carbon emissions was showcased.

5. Life cycle assessment analysis: environmental indicators comparison of different machining conditions

In order to close the gap between environmental considerations and manufacturing methods, the sustainability evaluation is now in use. An easy-to-use tool for evaluating how products, processes, and the rate at which materials are removed from the environment will affect sustainability It is almost always used in engineering fields where the environmental impact of processes and products has been assessed throughout the life cycle of the product. It addresses the goal and scope of the study, functional unit, system boundaries, and life cycle inventory handling.

5.1. Purpose of study and scope

ISO 14040 outlines the LCA set of norms and standards. LCA performed with the below-mentioned steps:

i. As ISO 14041 [44] defines, the first step is determining the assessment's aim and scope. It contains the LCA's goal, the description of the product under consideration, and the resources required for LCA execution.
ii. Inventory analysis specified in ISO 14041 is the second step. It depicts the material flow for the product. It also offers data on input variables, water, energy consumption, and transportation resource consumption at all four stages of the product life cycle.
iii. The third step is the sustainable impact analysis, as indicated by ISO 14042. The environmental and health repercussions of products are estimated in this step. This stage is regarded as the most significant because it impacts the findings of the LCA [45].
iv. The findings of the interpolation are expressed in the fourth and final phase [46] under ISO 14043 [32].

5.1.1. Functional unit and system boundaries

The Functional Unit (FU) is a critical indicator, especially compared to competing methodologies based on their environmental implications. Cutting time of 1 min was preferred as a functional unit. It is more preferred than metal removal in the Ecoinvent database and as per industrial specifications. The functional unit is directly related to the input and output of inventory and assessment indicators. It also acts as a reference to compare sustainable machining conditions, i.e. dry, flood, and MQL.

The Gate-to-Gate technique is used to evaluate environmental consequences based on a cooling strategy, which wipes out transportation and energy utilization to separate crude materials, handling of crude materials, use aluminium stock, and removal of material once its life is finished [47]. In this case, a streamlined LCA was used to assess solely the consequences caused by the cutting process on ecological parameters. As a result, the LCA study of machine tools, workplaces, and components required in cutting operations is negated because their environmental consequences are less dependent on the cutting conditions.

(Fig. 10) specifies the system boundary of the fundamentals being considered and the relationship among input-output flows during boring operations. Foreground and background procedures were characterized for the operations in which data was acquired from trials and the Ecoinvent database [48]; because of this motivation, ReCipe 2016 endpoint(H) was utilized for LCA. 18 different sustainable indicators were used to produce the précised results. This research isn't confined to a single effect category. An exploratory analysis used LCA to identify high-priority locations where the dry, flood, and MQL cutting conditions differed significantly. The differences in environmental and human health consequences across the cutting settings are highlighted in this priority category. For the internal turning process, processes related to the input-output processing units for cutting fluids have an insignificant impact for comparison purposes. Due to this reason, it was excluded from the research analysis.

The following procedure was left out when conducting the inventory check for the life cycle evaluation:

a) Components necessary in producing a workpiece are utilized in three distinct cutting circumstances, the Al 6061 alloy, the cutting tool, and manufacture.
b) Lack of suitable datasets prevents the manufacture of coated carbide bits from accurately enumerating the environmental impact of a coated carbide insert. It affects the precision of research work and highlights the importance of metalworking statistics. This absence, however, has no discernible impact on the study's conclusions. According to recent research, taking into account power and fluid use,

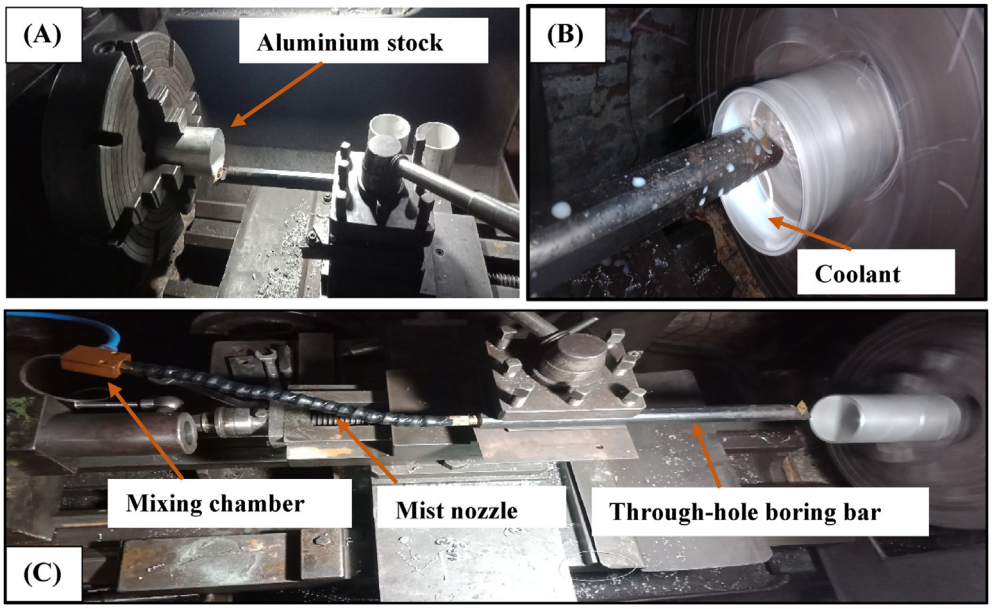


Fig. 5. Experimental set-up for dry, flood, and MQL machining.

Table 7
Results procured from sustainable machining trials.

Trial number	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Cutting Medium	Tool life (minutes)	Machining efficiency (%)	Energy consumption (KJ)	Carbon emissions (Kg-Co_2)
1	185	0.15	0.3	Dry	13.620	62.111	67.919	0.0162
2	185	0.15	0.3	Dry	13.640	62.426	63.377	0.0162
3	185	0.15	0.3	Dry	13.630	62.300	63.120	0.0162
4	185	0.2	0.5	Flood	21.430	58.545	51.667	0.0141
5	185	0.2	0.5	Flood	21.420	58.843	59.739	0.0142
6	185	0.2	0.5	Flood	21.440	58.723	59.497	0.0142
7	185	0.25	0.7	MQL	24.900	57.444	46.475	0.0121
8	185	0.25	0.7	MQL	24.800	57.736	58.615	0.0122
9	185	0.25	0.7	MQL	24.700	57.619	58.378	0.0122
10	215	0.15	0.5	MQL	18.630	59.586	51.485	0.0141
11	215	0.15	0.5	MQL	18.660	59.888	60.800	0.0142
12	215	0.15	0.5	MQL	18.640	59.767	60.554	0.0142
13	215	0.2	0.7	Dry	11.980	59.485	73.374	0.0172
14	215	0.2	0.7	Dry	11.960	59.787	60.697	0.0173
15	215	0.2	0.7	Dry	11.970	59.666	60.452	0.0172
16	215	0.25	0.3	Flood	19.870	57.212	58.030	0.0212
17	215	0.25	0.3	Flood	19.890	57.503	58.378	0.0213
18	215	0.25	0.3	Flood	19.880	57.386	58.142	0.0213
19	245	0.15	0.7	Flood	16.940	54.364	63.101	0.0192
20	245	0.15	0.7	Flood	16.960	54.640	55.472	0.0193
21	245	0.15	0.7	Flood	16.950	54.529	55.247	0.0193
22	245	0.2	0.3	MQL	17.240	58.556	57.465	0.0162
23	245	0.2	0.3	MQL	17.270	58.853	59.749	0.0162
24	245	0.2	0.3	MQL	17.250	58.734	59.507	0.0162
25	245	0.25	0.5	Dry	8.650	50.374	80.879	0.0242
26	245	0.25	0.5	Dry	8.630	50.629	51.4	0.0244
27	245	0.25	0.5	Dry	8.640	50.527	51.192	0.0243

Table 8
Inventory records for impact analysis.

Inventory input	Units	Details
Electricity	KWh	Electricity, high voltage {IN-Northern grid}| market for electricity, high voltage | Cut-off, U
Lubricants	Kg	Lubricating oil {RoW}| production | Cut-off, U
Compressed air	m^3	Compressed air, 600 kPa gauge {GLO}| market for | Cut-off, U

which are critical components of the life cycle evaluation, may still result in a thorough review [49].

c) Carbon dioxide is released when machining the aluminium stock, especially when using flood and mist lubrication. This parameter was included in the assessment technique as recorded through the machining trials.

d) All three cutting conditions have been simplified on related features to complete the inventory analysis. The amount of material removed is more significant due to the varied subsets of the cutting parameters, and the end product has a varying material removal volume. The aluminium alloy used in the metal component produced chips and

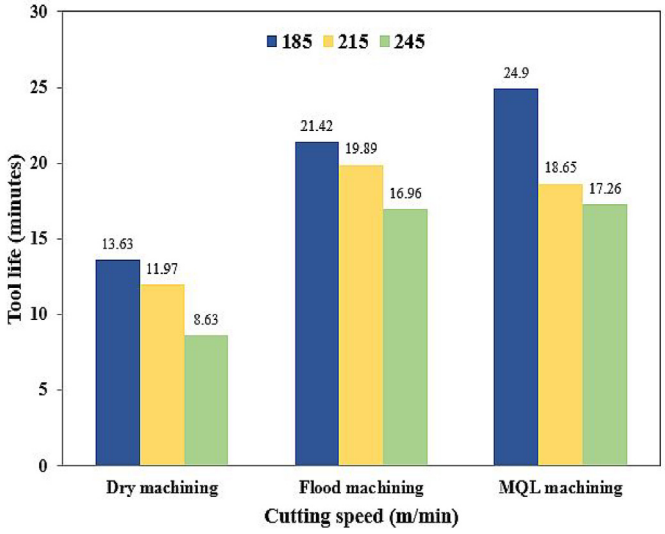


Fig. 6. Tool life under different cutting speeds and cutting environments.

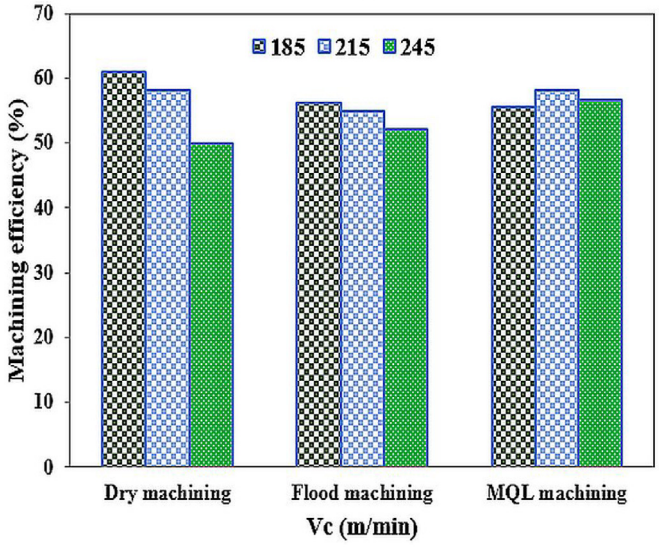


Fig. 7. Machining efficiency under different cutting speeds and cutting environments.

completed product are included in LCA calculations for streamlining (Fig. 11).

Regardless of the cutting fluid used, the machined object is expected to be used for the equivalent objective. This review does not include the usage stage, finished procedures, or destruction.

5.1.2. Inventory utilization

Electricity use, lubricant usage, and air compressor output were all measured during the experiment. The total quantity of material removed from the machining tests in different cutting settings estimates the effect evaluation on the chosen method and damages analysis (Table 8). lists the statistics for the study obtained from the Ecoinvent database.:

5.1.3. Inventory utilization results

The findings of the damage assessment and the environmental effect assessment are characterized by internal turning operation. Data mentioned in (Table 8) is given as a technosphere input for comparing the indicator results provided by the ReCipe endpoint 2016(H)

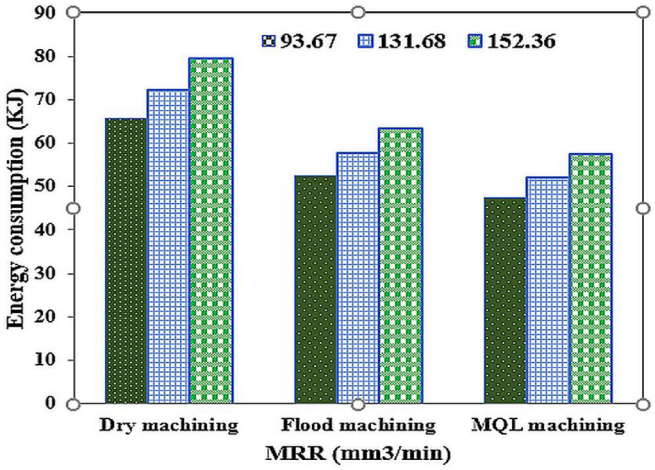


Fig. 8. Correlation of material removal rate and cooling strategy on total energy usage.

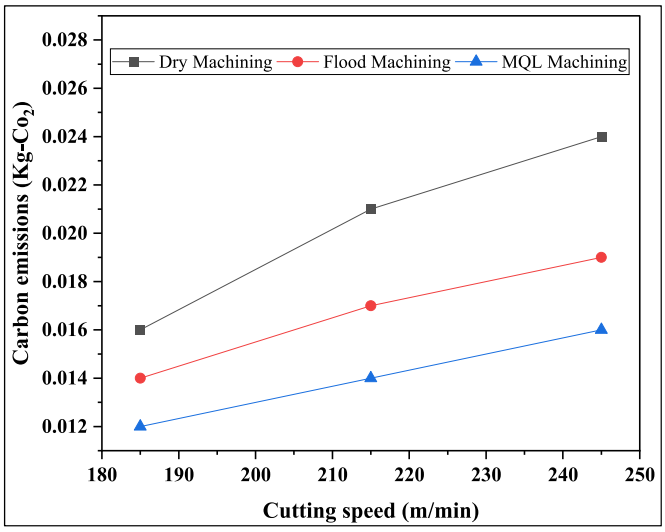


Fig. 9. Effect of cutting speed and lubrication conditions on carbon emissions.

methodology (Table 9). represents the comparative results of different machining conditions as per the Ecoinvent database. The radar diagram in (Fig. 11) demonstrates machining under dry conditions is more environmentally friendly than MQL and flood machining. It is due to less amount of electricity consumption and no coolant usage. With an increase in these two inventories' input, ecological indicators decrease abruptly, and ultimately, flood machining accounts most significantly for environmental impacts.

Similarly, for damage characterization, human health and ecosystems are worse affected in flood machining than in MQL and dry machining (Fig. 12) and (Table 10). As expected from the experimental trials, excessive usage of coolant and compressed air in flood conditions utilizes more resources than in dry and near-dry machining conditions. A similar kind of work has already been reported by Ref. [49] while using similar types of inventories for cryogenic machining.

5.1.4. Limitations of the life cycle assessment study

This analysis reflects one limitation of not using location-specific lubricant and compressed air, as mentioned in (Table 8). For lubricant global market specification utilized and for compressed air, RoW specified data employed for LCA analysis due to the non-availability of datasets. These datasets could be added to the Ecoinvent database for exact

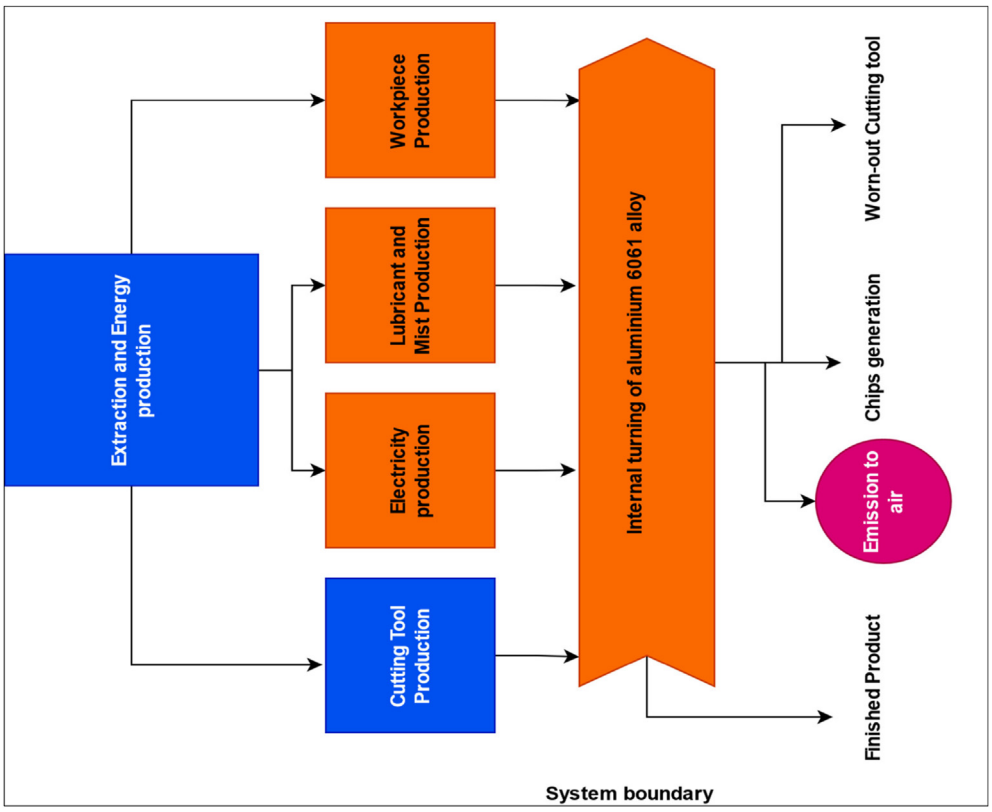


Fig. 10. System boundary assumptions for life cycle assessment.

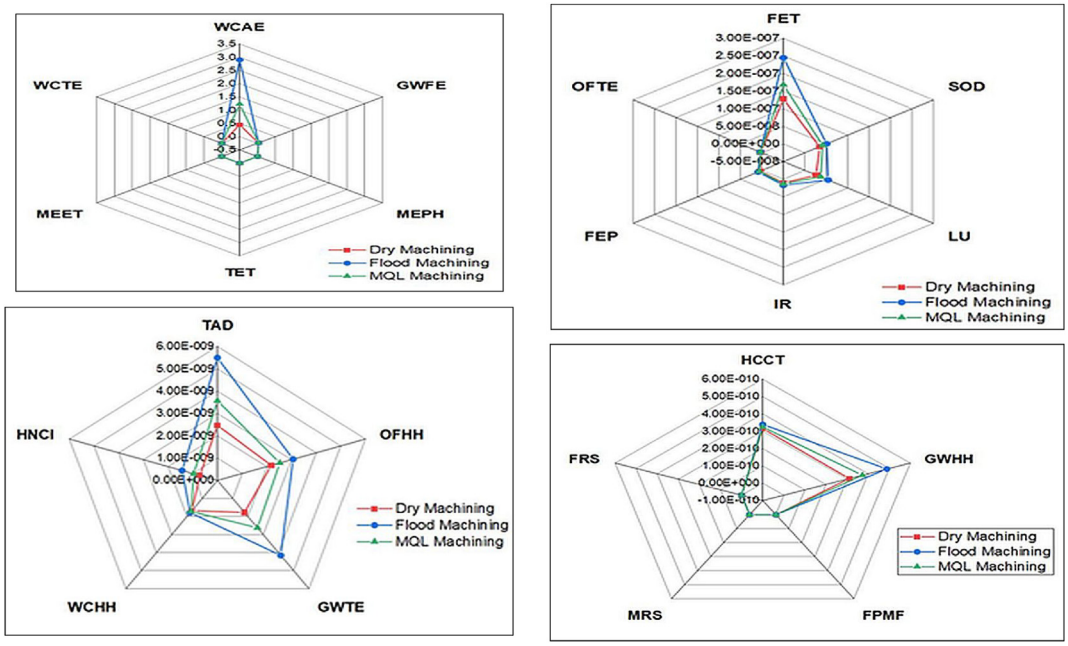


Fig. 11. Impact category comparison between the three lubricating environments.

ecological and damage assessment measurements.

6. Conclusions

The attempts in this paper were addressed to evaluate the sustainability features of machining aluminium alloy 6061 under different cooling methods. Under DM, FM, and MQL machining, numerous environmental sustainability factors such as energy consumption, carbon emissions, and machining efficiency have been researched. The following outcomes have been drawn based on the existing findings. ReCipe endpoint 2016(H) methodology was employed in this novel study to evaluate its endpoint impact categories and different cutting conditions depending on their environmental effects. The following statement can be made in conclusion based on the results:

Table 9
Processed outcome of Life cycle inventory analysis by ReCipe 2016.

Sustainability indicators	Dry	Flood	MQL
WCAE	0.446295248	2.894786623	1.228534727
GWFE	0.025276316	0.029656757	0.026704487
MEPH	1.5108E-05	2.30615E-05	1.87118E-05
TET	1.14466E-05	1.68921E-05	1.37951E-05
MEET	5.64461E-06	6.29877E-06	5.94589E-06
WCTE	2.90409E-06	3.99026E-06	3.3172E-06
FET	1.27713E-07	2.44696E-07	1.67599E-07
SOD	3.45428E-08	5.09771E-08	4.16301E-08
LU	2.65697E-08	5.44577E-08	3.68118E-08
IR	1.08775E-08	1.70753E-08	1.33206E-08
FEP	3.79969E-09	9.05197E-09	5.65674E-09
OFTE	2.9101E-09	4.16935E-09	3.54382E-09
TAD	2.46612E-09	5.49413E-09	3.56468E-09
OFHH	2.18029E-09	3.06603E-09	2.52884E-09
GWTE	1.77457E-09	4.15298E-09	2.62462E-09
WCHH	1.67895E-09	1.78713E-09	1.7213E-09
HNCI	7.14548E-10	1.43275E-09	9.63035E-10
HCCT	3.15225E-10	3.39062E-10	3.24476E-10
GWHH	3.10573E-10	4.88937E-10	3.72797E-10
FPMF	1.2653E-12	1.48789E-12	1.37192E-12
MRS	9.43388E-13	1.39223E-12	1.13696E-12
FRS	4.69181E-14	8.47677E-14	6.09106E-14

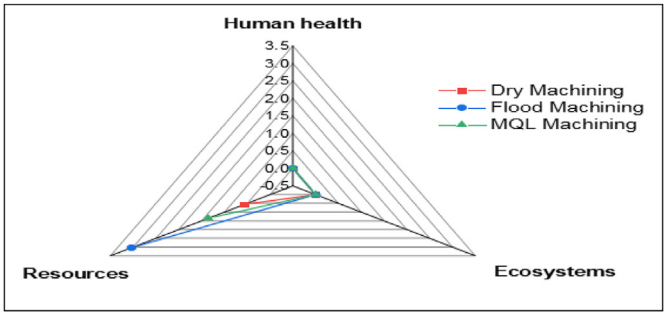


Fig. 12. Characterization of cooling conditions for damage impact indicators.

Table 10
Damage assessment characterization.

Sustainability indicators	Dry	Flood	MQL
Human health	4.45E-05	6.18E-05	5.21E-05
Ecosystems	7.17E-08	1.06E-07	8.57E-08
Resources	0.563933	3.036894	1.355779

- An increase of 42% and 61% in tool life at a cutting speed of 185 m/min under flood and MQL media than dry machining.
- At a cutting speed of 185m/min in three different lubricating conditions, the percentage increase in the machining efficiency was 31%, and 28% for dry, flood, and MQL machining.
- In MQL machining, due to more uniform lubrication than flood machining, energy usage decreases by 38%, 32%, and 27% at the rate of metal removal of 93.67, 131.68, and 152.36 mm^3/min.
- Also, a decrease in CO_2 emissions of 16%, 21%, and 18% was attained in MQL machining than flood machining at 185, 215, and 245 m/min cutting speeds.
- Dry machining outperforms flood and MQL machining in terms of sustainability in terms of global warming, freshwater ecosystems, water usage, and human health.
- Flood machining contributes more toward ecosystems and resources than dry and MQL machining.
- In Water consumption, aquatic ecosystems, marine ecotoxicity, stratospheric ozone depletion, and land use, flood machining dominates more than dry and MQL cutting conditions.

The current work is focused on the machining characteristics and ecological impact analysis of aluminium alloy under different cooling conditions. However, the constructed models may also be used for other machining operations using various cooling conditions. Furthermore, additional elements such as tool geometry, tool glazing, and multiple nanofluids could be explored in future research. Additionally, in this perspective, the life cycle approach (LCA) and other key sustainability frameworks may be utilized to study the ecological and economic implications.

Declaration of competing interest

All authors hereby declare that there are no financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work.

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