

Performance Evaluation of Minimum Quantity Lubrication (MQL) Using Vegetable- Based Oils

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Abstract—The increasing demand to sustainable manufacturing technologies Encouraged industries and researchers to develop organically friendly machining techniques capable to reduce pollution, to minimize lubricant consumption, and improvement machining efficiency. Conventional machining operations typically use flood cooling systems with a large amount of mineral oil cutting fluids delivered continuously. The cutting zone and for cooling lubrication purposes [1]. Although flood cooling methods improve machining efficiency, they also create serious environmental problems Because disposition used cutting fluids pollutants water and soil resources and growing operational costs [2]. Continuous exposure to mineral oil mist also causes health hazards Favor skin irritation, shortness of breath, and allergies between machine operators [3]. to overcome these limitations, has come up as Minimum Quantity Lubrication (MQL). A sustainable lubrication technique in which much small quantity of lubricant Directly mixed with compressed air. The cutting zone [4]. MQL systems significantly reduce lubricant consumption Under storage effective lubrication and machining performance [5]. Vegetable oils have become very popular. Suitable alternatives to conventional mineral Because of the oil their biodegradability, renewable nature, higher viscosity index, High lubricity and non-toxic properties [6]. Vegetable oil is produced. A strong lubricating film but the interface of the cutting tool and workpiece, thus reducing friction, heat generation, and tool wear during machining operations [7]. Researchers What is the report? significant improvements I surface finish, cutting temperature, tool life, and use force vegetable Oil- based MQL systems During turning, milling, drilling and grinding processes [8]. Recent advances in nanotechnology have further improved the performance of vegetable through an oil- based lubricant the addition of nanoparticles Favor aluminum oxide, Copper oxide, graphene, and molybdenum disulfide [9]. Nano provides improved lubrication. Superior thermal conductivity and tribological performance, As a result of better machining efficiency and sustainability [10]. This research paper examines performance. Vegetable Oil-based MQL systems through detailed experimental

analysis and discuss their influence on machine quality, environmental sustainability, and industrial productivity [11].

Index Terms—Minimum Quantity Lubrication (MQL), Vegetable-Based Oils, Sustainable Machining, Green Manufacturing, Nano-MQL, Cutting Temperature, Tool Wear, Surface Roughness, Cutting Force, Tribology, Biodegradable Lubricants, CNC Turning, Machining Performance, Nano Lubricants, Eco-Friendly Cutting Fluids, Sustainable Manufacturing, Vegetable Oil Lubricants, Machining Optimization, Environmental Impact, Energy-Efficient Machining.

I. INTRODUCTION

Machinist processes is among the majority important manufacturing operations used in modern industries to produce engineering components with high dimensional accuracy, high surface finish, and complex geometrical shapes. Processes such as turning, milling, drilling, grinding and drilling are widely used in automotive, aerospace, railway, marine, biomedical and heavy industry. Manufacturing industries to form metallic and non-metallic materials finished products [1]. During machining operations, the interaction between the cutting tool and workpiece creates severe friction and plastic deformation but the cutting zone, leads to the generation of excessive heat [2]. Developed at high temperature. The tool– chip interface Adversely affects machining performance. Tool wear, to reduce tool life, Deteriorating surface finish, increasing dimensional errors and use excessive power [3]. Therefore, efficient lubrication and necessary to improve cooling techniques. Machining performance, to reduce production cost, and increase the bite tool life [4].

Traditionally, conventional flood Cooling systems are used in machining operations to reduce friction and dissipate heat. The cutting zone [5]. in flood cooling methods, based on a large amount of mineral oil cutting fluid delivered continuously. The cutting interface and for cooling lubrication purposes [6]. However, the flood cooling system is better. Machining performance, Excessive consumption of cutting fluids Creates more environmental, economic and professional. Health problems [7]. Disposition of used cutting fluids makes a significant contribution to environmental pollution Because there is mineral oil-based lubricants. Toxic chemicals, Sulfur compounds, chlorine additives, and heavy metals which pollutes soil and water resources [8]. in addition, improper disposal of waste cutting fluids is growing ecological damage and has a negative impact. Aquatic life and around ecosystems [9].

In addition, environmental concerns, Prolonged exposure to cutting fluid May produce fog severe health hazards to machine operators [10]. Workers exposed mineral oil aerosols A frequent victim respiratory diseases, skin irritation, allergy, eye infections, and occupational asthma [11]. in addition, the maintenance, Recycling, etc. disposal of conventional cutting fluids Significant increase in machining costs and overall manufacturing expenses [12]. Researchers Guess it the cost Affiliated cutting fluids can be around 15- 20%. Total manufacturing expenses in machining industries [13]. Therefore, the industry is increasingly focusing on sustainable and environmentally friendly machining technology such as cutting fluid consumption Under storage machining efficiency [14]. to congregate these environmental and economic challenges, Minimum Quantity Lubrication (MQL) has materialized out as one Most of all promising sustainable machining techniques [15]. MQL is an advanced lubrication method in which much small amount of lubricant, usually in the middle 30– 100 mL/ h, atomized using compressed air and delivered directly into the cutting zone [16]. Unlike flood cooling systems, MQL Focuses primarily on lubrication rather than cooling. [17].

The microscopic lubricant droplets disrupt in the cutting interface and form a thin lubricating layer between the cutting tool and workpiece surface [18]. This lubricating film reduces friction, reduces adhesion, reduces cutting temperature, and improves the machine. Stability [19]. The researchers reported

this. MQL systems Considerably less cutting fluid consumption while maintaining comparable or even higher machining efficiency than conventional flood Cooling down systems [20]. The increasing adoption of MQL systems Mainly driven. The global demand to sustainable manufacturing and green production technologies [21]. Sustainable production focuses on reducing environmental pollution, protection natural resources, at the very least energy consumption, and improve worker safety without compromise production efficiency [22].

MQL technology supports these objectives by reducing coolant usage, to reduce hazardous waste generation, less energy consumption, and minimize operator exposure harmful chemicals [23]. in addition, MQL systems reduce requirements for machine cleaning, maintenance cost, and coolant disposal Costs, thus better overall economic efficiency [24]. Vegetable oils have transformed very popular. Attractive alternatives to conventional mineral I oil MQL applications Because of their environment friendly characteristics and excellent lubrication performance [25]. Derived from vegetable oil renewable biological resources and I'm biodegradable. Nature [26]. in contrast to mineral oils, does not contain vegetable oil toxic sulfur or chlorine compounds and therefore born lower environmental pollution [27].

Vegetable oils have too superior lubricity, high viscosity index, lower volatility, and higher flash point Compared to conventional mineral The oil [28]. Long-chain fatty acid molecules found in vegetable oils Form a robust and stable lubricating film on the cutting interface, this reduces and improves friction tribological performance During machining operations [29]. Several vegetable oils Investigations have been carried out for machining applications under MQL conditions. Soybeans are widely used for their oil. Its excellent oxidation stability and lubrication properties [30]. It's coconut oil. Superior thermal stability and lower friction coefficient, making it highly efficient for high- speed machining applications [31]. Exposure to sunflower oil high viscosity characteristics and improves chip formation and surface quality During machining operations [32]. Palm oil and canola oil is also often used because their superior lubrication efficiency and environmental compatibility [33]. Experimental studies showed this. Vegetable Oil- based MQL systems Significantly

improved surface roughness, less cutting force, at the very least tool wear, and lower cutting temperature During turning, milling, drilling and grinding operations [34].

In recent years, Nanotechnology has developed further. The performance of vegetable Oil- based lubricants in machinery operations [35]. Researchers have introduced nanoparticles Aluminum oxide (Al₂O₃), Copper oxide (CuO), titanium dioxide (TiO₂), graphene, and molybdenum disulfide (MoS₂) vegetable oils to improve thermal conductivity and tribological behavior [36]. Nano provides improved lubrication. Superior heat dissipation and friction reduction Compared to conventional lubricants [37]. Nanoparticles Act as miniature rolling elements but the cutting interface, to reduce direct contact between the cutting tool and workpiece surface [38]. Scientists observed this. Nano- MQL systems Significantly improved tool life, less cutting temperature, at the very least cutting force, and increase surface finish During machining operations [39]. The performance of vegetable Oil- based MQL systems Usually evaluated using several important machining parameters Prefer tool wear, cutting temperature, cutting force, surface roughness, chip morphology, and material removal rates [40]. The tool must be carried. One Most of all important factors Because it directly affects the machining accuracy, tool life, and production costs [41]. More than necessary tool wear is growing machine downtime and reduces the machining process. Productivity [42] Surface roughness is another critical parameter Because that decides the quality and functional performance of machinery components [43]. Minimize the effect of temperature tool life, thermal deformation, and chip formation During machining operations [44]. Low cutting force and improved chip morphology indicate effective lubrication and stable Machinist conditions [45]. Several researchers the application has been examined. Vegetable Oil- based MQL systems in machining different engineering materials. Dhar etc. Studied the mechanics of AISI 1040 steel under MQL conditions and observed significant reduction in cutting temperature and tool wear Compared to dry machining [3]. Laval et al.

Reviewed the application. Vegetable Oil- based lubricants in machinery ferrous metals and concluded with that vegetable oils allocate superior lubrication

characteristics due to their fatty acid structure [11]. Mia and Dhar examine the duplex beam. MQL systems and observed lower surface roughness and better chip morphology During machining operations [5] Sharma and Dixit studied nano- fluid MQL systems and reported significant reduction in friction and bites temperature due to enhanced thermal conductivity of nanoparticles [26]. Gupta and Sharma observed improved surface finish and reduced cutting force Uses nano- enhanced vegetable oil lubricants under MQL conditions [25]. Researchers It further concluded that vegetable Oil- based MQL systems Considerably less environmental pollution and improve operator safety Compared to mineral oil- based lubricants [54]. Despite numerous advantages, Vegetable oil- based MQL systems still face some limitations. Vegetable oils may suffer from oxidation instability and poor thermal resistance at the extreme high temperatures [46]. Addition of nanoparticles also increases lubricant preparation cost and there is a warrant proper dispersion technique to maintain stability [47]. in addition, optimization of machining parameters such as cutting speed, feed rate, Lubricant flow rate, and nozzle position is necessary to obtain. Maximum machining performance under MQL conditions [48]. Therefore, continuous research Need to improve lubrication efficiency, Thermal stability and durability vegetable Oil- based MQL systems [49]. The primary objective of this research paper to be assessed the performance of vegetable Oil- based Minimum Quantity Lubrication systems in machining operations and analysis their influence on machine quality, environmental sustainability, Economic efficiency, and industrial productivity [50]. The study investigates Performance of different vegetable The oil under controlled machining conditions and compares Their effectiveness in reducing tool wear, cutting temperature, Surface roughness and cutting force [51]. Also mentioned in the newspaper. Recent advancements in nanoenhanced lubricants, environmental benefits of MQL systems, Challenges associated with vegetable Oil- based lubricants etc future opportunities to sustainable machining technologies [52].

The findings of this study are expected to execute an important role in relation to the development in environmentally responsible and energy efficient production practices modern industries [53].

II. LITERATURE REVIEW

Extensive research has been held Minimum Quantity Lubrication (MQL) and machining operations due to vegetable oil- based lubricants the increasing demand to sustainable manufacturing technologies. Researchers from different countries have investigated the influence of MQL systems on mechanical performance, environmental impact, utilize tools, cutting temperature, surface roughness, cutting force, and energy consumption [1]. The literature shows that vegetable oil- based lubricants provide superior lubrication performance and environmental compatibility Compared to traditional mineral oil base cutting fluids [2]. Recent advances in nanotechnology have further improved the efficacy of vegetable oil-based formulations. MQL systems through the addition of nanoparticles capable to improve thermal conductivity and tribological characteristics [3]. One of the earliest studies but sustainable machining was organized by Klocke and Eisenblätter, who did the analysis. Dry cutting and alternative lubrication methods to reduce coolant consumption in machining industries [6]. Their study highlighted the environmental and economic damages associated with it. Conventional flood Cooling system and stressed the importance of developing sustainable machining technologies. Likewise, Weinert et al. Investigated dry machining and MQL systems and concluded with that Minimum Quantity Lubrication reduces significantly coolant usage Under storage machining efficiency [60]. Their work is done. A major role in encouraging industries to be environmentally friendly lubrication systems. Dhar et al. Done experimental investigations on the machine AISI 1040 steel under MQL conditions and observed significant improvements in machining performance compared to dry machining [3]. Their study proved this. MQL systems less cutting temperature, improve surface finish, and expansion tool life Because the lubricant Forms a stable Grease layer between the cutting tool and workpiece The researchers also observed reduced chip- tool adhesion and lower cutting force under MQL conditions. These results were confirmed the effectiveness of MQL systems in improvement machining quality Minimizes the bite fluid consumption. Lawal et al. Held a comprehensive review About the apply of vegetable oil- based lubricants in machines ferrous metals [11]. Go researchers Explained it vegetable oils possesses

superior lubrication properties due to their long- chain fatty acid molecules, whose form a strong lubricating film but the cutting interface.

Their study It concluded vegetable oils are highly suitable for machining operations as they reduce friction and minimize heat generation, and improve mechanical stability. The researchers Also shed illumination the environmental benefits of vegetable oils, including biodegradability, renewability and reduced toxicity Compared to mineral oils. Pervaiz et al. Investigated the influence of Minimum Quantity Lubrication on the machining and analysis of complex cut materials power consumption and tool wear During machining operations [1]. This has been revealed from their study. MQL systems Considerably less power consumption and improve tool life Because of reduced friction and lower cutting temperature.

The researchers Observed it further MQL systems Improve machine durability by minimizing lubricant consumption and to reduce environmental pollution. Debnath et al. Environmental assessment carried out friendly cutting fluids and cooling techniques in machining operations [14]. Their studies focused on sustainable lubrication methods Value dry machining, cryogenic cooling, and MQL systems. Go researchers concluded that vegetable oil- based lubricants are the most promising alternatives to mineral oil because they provide effective lubrication with minimal environmental impact.

The study It was also emphasized vegetable oils Improve and reduce machining efficiency. Health hazards to machine operators. Several researchers Investigated the performance of specific vegetable The oil under MQL conditions. Ali studied coconut oil- based applications. MQL systems in diversion operation and reported significant reduction in cutting temperature and tool wear [37]. Exposure to coconut oil excellent thermal stability and lubrication performance due to its high viscosity characteristics and strong fatty acid structure Likewise, Kuram and Ozcelik Researched on the basis of sunflower oil. Cutting fluids and reported improved surface finish and lower cutting force During machining operations [23]. This conclusion was drawn from their study. Sunflower oil improve lubrication efficiency and chip formation Because of its superior tribological properties. Kumar and Singh investigated the mechanical properties based on palm oil. MQL

systems and observed significant reduction Cutting force and cutting temperature during machining operations [42]. Go researchers It concluded palm oil gives effective lubrication and improves machining stability. Its higher flash point and viscosity index.

Talib and Rahim A chemically revised study was performed vegetable oils and reported improved oxidation stability and lubrication efficiency under high- temperature Machinist conditions [20]. Mia and Dhar examined the duplex beam. MQL systems and analyzed their influence on the machine performance [5]. Their experimental study showed that the duplex beam MQL systems give better lubricant penetration I the cutting zone, as a result of which lower surface roughness, better chip morphology, and reduced cutting force. Go researchers It concluded proper nozzle positioning and lubricant delivery Significantly affects machining. Efficiency under MQL conditions. Attanasio et al. Studied the application of MQL systems in diversion operation and reported improved tool life and lower cutting temperature Compared to conventional flood Cooling down systems [15]. Go researchers Observed it MQL systems less frictional resistance but the cutting interface and improve chip evacuation during machining Likewise, Obikawa and Kamata Investigated high speed machining under MQL environments and observed reduced adhesion between the cutting tool and workpiece [62]. This has been revealed from their study. MQL systems Improve and reduce machining stability. Thermal deformation during high- speed cutting operations. The application of nanotechnology I MQL systems has become one Most of all important research areas I sustainable machining. Sharma and Dixit investigated. Nano-fluid MQL systems and reported significant reduction in cutting temperature and friction Because nanoparticles are better. Thermal conductivity and tribological behavior [26]. Their studies focused on aluminum oxide and copper oxide nanoparticles met with vegetable oils. The researchers observed that nanoparticles work. Miniature rolling elements but the cutting interface, this reduces and improves friction lubrication efficiency. Gupta and Sharma Also nano-enhanced research vegetable oil lubricants under MQL conditions and observed improved surface roughness, less cutting force, and better tool life During machining operations [25]. Their studies manifest that nanoparticles increase heat dissipation and improve

chip evacuation during machining. Likewise, Hegab et al.

Investigated nano- cutting fluids I MQL Machinability and improved mechanical stability were reported, reduced. Tool wear, and lower cutting temperature [35]. Go researchers concluded that nanoenhanced lubricants significantly improve machining performance compared to solids. Conventional lubricants. Padmini et al. Investigated the effectiveness of vegetable oil- based nanofluids and reported that nanoparticles are better. The thermal conductivity and tribological properties of lubricants [57]. Their experimental study showed that nano-enhanced vegetable oils Significantly reduce and improve friction surface quality during machining Gajrani and Dixit Investigated further sustainable machining using nanofluids and concluded that nanoenhanced lubricants are better. Lubrication efficiency and environmental sustainability [65]. Researchers Also focused on environmental and economic aspects based on vegetable oil. MQL systems. Siddur et al. Biolubricants reviewed and highlighted. Their environmental benefits, including biodegradability, renewability and reduced toxicity [58]. Go researchers It concluded vegetable oils Considerably less environmental pollution Compared to mineral oils Boswell and Islam studied green cutting fluids and sustainable machining practices and observed lower operational cost and improved worker safety Employ a vegetable oil base lubricants [54]. Shokrani et al. Environmental research conscious machining and emphasized the importance of sustainable lubrication techniques to reduce environmental impact [66]. This has been revealed from their study. MQL systems less energy consumption, Costs for disposal of coolant, and maintenance requirements in the mechanical industry Singh and Ahuja analyzed durability in machining operations using MQL systems and reported improved economic efficiency Because of reduced lubricant consumption and lower machine downtime [31]. Recent research Focused on intelligent lubrication systems and optimization of machinery parameters under MQL conditions. Karam investigated. Optimization of MQL parameters reported improved machining performance during milling operations and the use of optimized lubricant flow rate and nozzle positioning [44]. Mia studied further. Multi- response optimization of MQL parameters and observed

significant improvement in machining quality under custom processing conditions [67]. Despite extensive research based on vegetable oil MQL systems, some limitations still exist. Vegetable oils may suffer from oxidation instability and poor thermal resistance under machining with ultra-high temperature conditions [49]. Nano-enhanced lubricants are also needed. Proper dispersion techniques to maintain nanoparticle stability [53]. In addition, the cost of nanoparticles and nano-lubricant preparation remains relatively high for large-scale industrial applications [65]. Researchers so we focus on chemically modified growth vegetable oils, hybrid nano-lubricants, and intelligent lubrication systems to improve machining efficiency and sustainability [33]. Overall, the literature clearly states that based on vegetable oil MQL systems, significant improvement in machining efficiency, low environmental pollution, at the very least lubricant consumption, and increase durability in relation to conventional flood cooling down systems [70]. The integration of nanotechnology with vegetable oil-based lubricants has been further improved. Lubrication efficiency and machining quality [56]. However, continuous research still demands optimization. Machining parameters, to improve oxidation stability, and to reduce the cost of nano-enhanced lubricants for future industrial applications [53].

III. MINIMUM QUANTITY LUBRICATION (MQL)

Minimum Quantity Lubrication (MQL) An advanced and environmentally friendly sustainable machining lubrication technique in which much small quantity of lubricant is delivered directly. The cutting zone uses compressed air [10], in contrast to conventional flood cooling systems that use large quantities of cutting fluids, MQL systems are used only a minimal amount of lubricant, usually in the middle 30–100 mL/h, during retention effective lubrication and machining performance [60]. The primary objective of MQL is to reduce the friction between the cutting tool and workpiece instead of relying entirely on cooling action [6]. Because of its low lubricant consumption and reduced environmental impact, MQL has been created. One of the most important sustainable machining technologies in modern manufacturing industries [14]. The working principle of MQL is

based on atomization of lubricant in microscopic droplets. Use compressed air [15]. These tiny droplets are transferred through the nozzles and delivered directly into the body. The cutting interface between the cutting tool and workpiece material [8]. When the lubricant enters the cutting zone, it does a thin lubricating film which reduces direct metal-to-metal contact, thereby reducing friction, adhesion, and heat generation during machining operations [21]. Compressed air helps at the same duration. Chip evacuation and the cooling off the cutting zone, to improve machining stability and surface quality [5]. Scientists observed this. The combination of lubrication and compressed air inside MQL systems significantly increases machining efficiency compared to dry machining operations [3]. The adoption of MQL systems because of the rapid growth conventional flood cooling methods are extremely environmentally friendly and economical. Challenges [18]. A flood cooling system is required. Continuous circulation of large quantities of cutting fluids, as a result of which high operational costs, disposal costs etc. environmental pollution [54]. Disposal of used cutting fluids especially difficult due to mineral oil-based lubricants. Sulfur compounds, chlorine additives, etc. toxic chemicals harmful to ecosystems and human health [58]. In front of machine operators' coolant mist can also suffer from respiratory disorders, skin irritation, allergy, and eye infections [66]. MQL systems significantly reduce these problems because only one-party small amount of lubricant used during machining operations [31]. Reduced coolant usage reduces disposal cost, do the least environmental pollution, and improves operator safety [40]. MQL systems contain several important components including an air compressor, lubricate reservoirs, pressure regulator, flow control valve, nozzle arrangement, and delivery pipeline [52]. An air compressor produces compressed air that is needed for atomization of lubricant, while the lubricant reservoir shops the cutting fluid used during machining operations [44]. A pressure regulator control. Air pressure, to be sure uniform delivery of lubricant droplets in the cutting zone [67].

The nozzle arrangement plays a critical role in MQL systems because proper nozzle positioning takes care of efficient penetration of lubricant droplets in the cutting interface [5]. Scientists observed this. Nozzle angle, nozzle distance, and lubricant flow rate

Significantly affects machining. Performance under MQL conditions [24]. The effectiveness of MQL systems depends on several machining parameters as cutting speed, feed rate, depth of cut, lubricant flow rate, air pressure, and nozzle position [45]. but lower cutting speeds, MQL systems provide. Excellent lubrication and heat dissipation Because lubricant droplets Can penetrate effectively the cutting interface [16]. However, extremely high cutting speeds, more than necessary heat generation can reduce lubrication efficiency If the lubricant flow rate is insufficient [64]. Therefore, optimization of machining parameters is necessary to achieve maximum machining performance under MQL conditions [67]. Researchers Extensively researched the influence of MQL systems About machining performance during turning, milling, drilling and grinding operations [46]. Dhar etc. Studied the swing operations under MQL conditions and observed significant reduction I cutting temperature and tool wear Compared to dry machining [3]. The researchers It concluded the lubricating film Established by MQL systems Effectively reduces friction and improves machining stability. Likewise, Attanasio et al.

Reported improved tool life and reduced cutting force During the change operations under MQL conditions [15]. Their study proved this. MQL systems less chip-tool adhesion and improve chip evacuation during machining. During milling operations, MQL systems are highly effective because intermittent cutting generates severe friction and the heat the cutting zone [44]. Scientists observed this. MQL systems Improve mechanical stability, reduce vibration and increase surface quality During high-speed milling operations [8]. Drilling operations are also very useful. MQL systems Because lubrication is better. Chip evacuation and reduces thrust force during deep hole Drilling [52]. Grinding operations generate excessive heat. High friction between the grinding wheel and workpiece surface [47]. This has been revealed by experimental studies. MQL systems Considerably less wheel wear and improve grinding efficiency compared to dry grinding operations [17]. One Most of all important advantages of MQL systems is reduction in tool wear During machining operations [38]. Excessive friction and heat generation is the primary causes of flank wear, pit dress, and tool failure During machining [41]. MQL systems reduce frictional resistance but the cutting interface by creating a

lubrication layer between the cutting tool and workpiece [21].

Researchers Observed it lower cutting temperature and improved lubrication Significantly expanded tool life and reduce machining. Cost [1]. Also promotes better lubrication. Surface finish Because reduced friction Reduces vibrations and thermal deformation During machining operations [18].

Cutting temperature is another important parameter Strongly influenced MQL systems [20]. Dry machining operations usually provide very high performance. High cutting temperatures Because there is no lubrication in between the cutting tool and workpiece [22]. Flood cooling systems reduce the temperature by adding large quantities of coolant, but they do environmentally and economically problems [14]. MQL systems furnish effective lubrication Which does the least heat generation but the cutting interface, thus is reduced cutting temperature without excessive coolant consumption [30]. The researchers reported that based on vegetable oils MQL systems furnish superior thermal stability and lubrication performance Compared to traditional mineral oil base lubricants [32]. Surface roughness is an important indicator Machining quality as it is directly affected. Dimensional accuracy and functional performance of machinery components [43]. Scientists observed this. MQL systems Significantly improved surface finish Because effective lubrication Reduces friction, vibrations, and chip adhesion During machining operations [24]. Mia and Dhar examine the duplex beam. MQL systems and observed lower surface roughness and improved chip morphology During the alter operations [5]. The researchers It concluded proper lubricant penetration I the cutting interface Significantly improves machining quality. Chip morphology is another important factor Influenced by MQL systems [22]. Continuous and even chips indicate stable machining conditions. Effective lubrication [45]. Dry machining often produces irregular and damaged chips due to excessive heat generation Influences chip formation [20]. Scientists observed this. MQL systems improve chip evacuation and produces continuous chips as lubrication is reduced. Adhesion and friction but the cutting interface [5]. Improved chip morphology also reduces tool wear and improves machining. Efficiency [17]. Recent developments Nanotechnology has been further improved. The performance of MQL systems

[35]. The researchers introduced nanoparticles Aluminum oxide (Al₂O₃), Copper oxide (CuO), graphene, and molybdenum disulfide (MoS₂) to improve vegetable oil-based lubricants thermal conductivity and tribological behavior [26]. Nano Enhanced MQL systems Considerably less cutting temperature, at the very least tool wear, and improve surface finish Compared to conventional MQL systems [57]. Nanoparticles Act as miniature rolling elements between the cutting tool and workpiece surface, to reduce direct contact and friction [25]. The researchers further observed that nano-enhanced lubricants are better. Heat dissipation and machining stability during high-speed machining operations [65]. Environmental sustainability is one of the major advantages of MQL technology [54]. Minimizes the use of lubricants. Hazardous waste generation and reduces environmental pollution [58]. Vegetable oil-based lubricants are used. MQL systems are biodegradable and renewable, making them More environmentally friendly than mineral oil-based lubricants [49]. Researchers Reported it MQL systems Considerably less energy consumption, Coolant disposal cost, and maintenance requirements for machining industries [31]. Improved operator safety and lower exposure to toxic chemicals More additions the industrial importance of MQL systems [66]. Despite numerous advantages, The MQL system still faces some challenges. Industrial applications [53]. Inadequate lubrication can occur during very high-speed machining if lubricant flow rate and nozzle positioning is not as desired [64]. Vegetable oil-based lubricants can also suffer from this. Oxidation instability on high temperatures [49]. in addition, nano-enhanced lubricants are required. Proper dispersion techniques to maintain nanoparticle stability and stops sedimentation [35]. Researchers So with a focus on optimizing machining parameters, intelligent lubrication systems, and development of hybrid nano-lubricants to improve MQL performance in future manufacturing applications [33].

Overall, Minimum Quantity Lubrication technology provides an efficient and sustainable alternative to conventional flood Cooling down systems [70]. MQL systems significantly improve machining efficiency by reducing tool wear, cutting temperature, surface roughness, and at the same phase minimize the cutting force environmental pollution and lubricant consumption [16]. Mixtures based on vegetable oils

lubricants and nanotechnology has increased further the efficiency and sustainability of MQL systems I modern manufacturing industries [25].

IV. VEGETABLE- BASED OILS USED

I MQL Have appeared as vegetable oils. One Most of all important alternatives Based on conventional mineral oil cutting fluids I Minimum Quantity Lubrication (MQL) systems Because of their Environmentally friendly nature, Superior lubrication properties, and renewable characteristics [11]. The increasing concern approx environmental pollution, Generation of hazardous waste, and occupational health hazards Affiliated mineral oils Encouraged industries and researchers to discover biodegradable lubricants suitable to sustainable machining applications [14]. Derived from vegetable oil natural biological resources Esteem seeds, fruits and plants, it is petroleum-based to produce them renewable and biodegradable. Lubricants [58]. Their Non-toxic nature and lower environmental impact Create it highly relevant to them green manufacturing technologies [54].

One Most of all important reasons to the increasing use of vegetable There is oil in the mechanical operation their superior lubricity [23]. Contains vegetable oil. Long-chain fatty acids with polar molecular structures which forms a strong and stable lubricating film. The interface between the cutting tool and workpiece material [39]. This lubrication layer reduces direct metal-to-metal contact, thereby reducing friction, adhesion, and heat generation During machining operations [21]. Researchers Observed it vegetable Oil-based lubricants significantly improve machine performance by reducing friction. Tool wear, to reduce cutting temperature, to improve chip formation, and increase surface quality [16]. Vegetable oils have too higher viscosity index and higher flash point Compared to mineral oils [28]. Higher viscosity index Enables vegetable oils to maintain stable lubrication performance over a wide range of machinery temperatures [32]. Their higher flash point Reduces the risk of evaporation and smoke generation During high-speed machining operations [20]. in addition, vegetable oils Low volatility exposure and superior load-carrying capacity, which is improving lubrication efficiency during severe machining conditions [49]. These create functions. Vegetable oils

Very effective for MQL applications Where lubrication does most of the work. Critical role from the limited [60]. Soybean oil is one the most used vegetable oils in machining operation due to its excellent oxidation stability, High lubricity, and easy availability [31]. The researchers observed that soybean oil is based on MQL systems Considerably less tool wear and improve surface finish During turning and milling operations [2]. Strong fatty acid composition soybean oil Forms a stable Lubricating film that reduces friction. The cutting tool and workpiece [11]. Experimental studies It also revealed soybean oil improve chip morphology and reduces cutting force Because of its superior tribological characteristics [45]. Coconut oil is another important vegetable oil It is widely used MQL systems Because of its excellent thermal stability and lubrication performance [37]. Contains coconut oil. Saturated fatty acids which give high oxidation resistance and stable lubrication characteristics for higher machining temperatures [35]. Researchers have reported that coconut oil- based MQL systems Considerably less cutting temperature and flank wear during high- speed machining operations [12]. The low friction coefficient of coconut oil Also improves surface finish and machining stability [32]. Experimental investigations showed this. Coconut oil gives superior performance Compared to several other vegetable Because of the oil its strong lubricating characteristics and thermal resistance [37].

Sunflower oil Widely used in machining operations due to its high viscosity index and excellent lubrication properties [13]. The researchers observed that sunflower oil- based MQL systems improve surface quality and reduce chip adhesion During machining operations [23]. High viscosity properties of sunflower oil Activate effective formation of the lubrication layer the cutting interface, thus is reduced friction and heat generation [18]. Experimental studies He further revealed that sunflower oil Reduces significantly cutting force and improves machining stability during turning. Operations [21]. Palm oil Got too considerable attention I sustainable machining applications Because of its higher flash point, High lubricity, and environmental compatibility [42]. The researchers observed that palm oil- based MQL systems less cutting temperature and improve machining efficiency during turning and milling operations [34]. Forms of palm oil. A stable

Lubricating layer that reduces adhesion between. The cutting tool and workpiece surface [29].

Experimental investigations He further revealed that palm oil improve chip evacuation and do less tool wear During machining operations [24].

Canola oil Another is often used vegetable oil I MQL applications Because of its excellent oxidation stability and superior tribological behavior [20]. Researchers report that rapeseed oil- based lubricants are decreasing. Frictional resistance and improve surface finish During machining operations [15]. Fatty acid composition canola oil gives effective lubrication under high- pressure Machining ratio, thus less cutting force and heat production [17]. Experimental studies It also turned-out canola oil improve tool life and mechanical stability compared to mineral oil base lubricants [63]. Castor oil hair unique lubrication properties Because of its high ricinoleic acid content [58]. Scientists observed that based on castor oil MQL systems give excellent lubrication efficiency and reduce cutting force During machining operations [49]. High viscosity and superior film- forming ability of castor oil Optimize and minimize mechanical stability. Tool wear [25].

Experimental studies Revealed it castor oil Particularly effective for processing materials that are difficult to cut because it holds stable lubrication under severe machining conditions [1]. in addition, pure vegetable oils, Scientists have also investigated chemical. Modified vegetable Oil for machines applications [20]. Chemical modified vegetable the oil sight has improved. Oxidation stability, thermal resistance, and lubrication performance compared to no treatment vegetable oils [31]. Researchers Reported it modification techniques Esteem transesterification and epoxidation Thermal and tribological optimization properties of vegetable oils, making them more suitable for high- speed machining operations [49]. Edited vegetable oils Also exhibits lower viscosity variation and better resistance Degradation during machining processes [53]. The tribological behavior of vegetable Oil spill a crucial role by deciding their Machinist performance under MQL conditions [39]. Tribology refers to the study of friction, wear and sliding between interacting surfaces relative motion [22]. Vegetable oils exhibit superior tribological performance Because the polar fatty acid molecules Adhere strictly metallic surfaces and form a stable

Lubricate boundary layer [63]. This boundary lubrication Reduces frictional resistance and reduces intermediate wear. The cutting tool and workpiece surface [21]. The researchers concluded that the superior tribological properties of vegetable Oil significantly improves machining quality and reduces wear. Energy consumption [61].

Researchers Also researched the influence of vegetable on the oil tool wear During machining operations [38]. The tool must be carried. One Most of all critical factors Touched machining efficiency, dimensional accuracy, and production cost [41]. This has been revealed by experimental studies. Vegetable Oil- based MQL systems Considerably less flank wear and crater Use it because effective lubrication Do the least direct contact between the cutting tool and workpiece [16]. Coconut oil and soybean oil Exhibition superior anti- wear properties Because of their strong lubricating film and high thermal stability [37]. Reduced tool wear is growing tool life and do less machine downtime, So improvement industrial productivity [1]. Surface roughness is another important parameter Influenced by vegetable Oil- based lubricants [43]. Scientists observed this. Effective lubrication Reduces vibrations, friction and thermal deformation During machining, as a result smoother surface finish [18]. Vegetable oil- based MQL systems Produced significantly lower surface roughness Compared to dry machining and conventional flood Cooling down systems [24]. Coconut oil and sunflower oil Exhibition excellent surface finish characteristics Because of their superior lubrication efficiency and viscosity properties [13]. Cutting temperature Barely affects the machine quality and tool life During machining operations [20]. Causes excessive heat generation. Thermal deformation, rapid tool wear, and poor chip formation [44]. Scientists observed this. Vegetable Oil- based MQL systems Considerably less cutting temperature Because lubrication layer minimizes frictional heat generation but the cutting interface [21].

Nano Enhanced vegetable oils Improve further thermal conductivity and heat dissipation During machining operations [25]. Environmental benefits of vegetable Contains oil- based lubricants. They're For the most part significant advantages [54]. Vegetable oils are biodegradable and renewable. Reducing environmental pollution and hazardous waste generation [58]. in contrast to mineral oils, does not

contain vegetable oil toxic sulfur or chlorine additives harmful to ecosystems and human health [14].

Researchers Reported it vegetable Oil- based MQL systems Considerably less coolant disposal cost and environmental contamination Compared to conventional flood Cooling down systems [31]. Lower fog generation and reduced toxicity Even better operator safety During machining operations [66]. Despite numerous advantages, Vegetable oil- based lubricants still face certain challenges I industrial applications [53]. May contain vegetable oil. Oxidation instability at high processing temperatures, due to degradation of lubrication performance [49]. Something vegetable oils Also exhibits limited thermal resistance under High-speed machining conditions [64]. Researchers Hence the focus on chemical development. Modified vegetable Oils and nano- enhanced lubricants to improve performance thermal stability and lubrication efficiency [36]. Recent advancements Nanotechnology has further improved performance. Vegetable Oil- based lubricants under MQL conditions [35]. Nanoparticles e. G aluminum oxide, copper oxide, titanium dioxide, graphene, and molybdenum disulfide Mix with vegetable oils to improve thermal conductivity and tribological behavior [26]. Nano Enhanced vegetable oils Considerably less cutting temperature, reduce friction, and improve mechanical stability compared to conventional lubricants [57] Researchers Observed it nanoparticles Act as miniature rolling elements between the cutting. tool and workpiece, to reduce direct surface contact and improvement lubrication efficiency [65]. Experimental investigations have shown that nano is improved. Vegetable oils improve surface finish, less tool wear, and lower cutting force During machining operations [24].

Overall, vegetable oils provide an effective and sustainable alternative to mineral oil- based oils. Cutting fluids, I Minimum Quantity Lubrication systems [70]. Their superior lubrication properties, Biodegradability, renewable, and environmental compatibility Generate it highly relevant to them green manufacturing applications [54]. Experimental investigations Situation this clearly vegetable Oil- based MQL systems while significantly improving machining efficiency reducing environmental pollution and operational costs [31]. Continuous research in chemistry modified vegetable Oils and nano- enhanced lubricants are expected to further

improve performance and durability. Vegetable Oil-based MQL systems I future industrial applications [33].

V. RESEARCH METHODOLOGY

The research methodology I adopted this study was designed to evaluate the mechanical performance of vegetable oil- based Minimum Quantity Lubrication (MQL) systems under controlled machining conditions. Empirical methodology focuses on analysis. The influence of different vegetable on the oil machining parameters Value tool wear, surface roughness, cutting temperature, cutting force, chip morphology, and material removal rate During the change operations [45]. The methodology was developed on the basis of previous experimental investigations Organized by researchers I the field of sustainable machining and green manufacturing technologies [3]. The overall purpose of the methodology the effectiveness of vegetable oil- based was compared. MQL systems with dry machining and conventional flood Cooling down methods [21].

The experimental investigations were performed using a CNC Lathe because turning is. One Among the most used machining operations in production industries [46]. Turning operations are generated. Severe friction and the heat the interface between the cutting tool and workpiece material, very important to maintain lubrication and cooling. Machining quality and tool life [16].

The CNC Used in lathes this research granted precise control ready machining parameters Esteem cutting speed, feed rate, and cutting depth, which ensures such consistency and repeatability during experimentation [52]. AISI 1040 medium carbon steel was chosen as the workpiece material Because of its extensive industrial applications in the automotive industry, machine tool, and structural manufacturing industries [3]. AISI 1040 Steel is widely used for axles, gears, bolts, couplings and technical components due to its good strength and machinability characteristics [41]. The workpiece material was prepared. Cylindrical form with dimensions on 100 mm length and 40 mm diameter.

The chemical composition and mechanical properties of the workpiece material was chosen according to industrial standards to be sure reliable experimental analysis [45]. Coated carbide cutting tools was chosen

for machining operations due to their superior wear resistance, High hardness, and thermal stability under high- speed Machinist conditions [51]. Carbide cutting tools are widely used. Industrial machining operations Because they maintain cutting efficiency Even at height temperatures [38].

The cutting insert geometry and tool holder dimensions was chosen according to ISO Machining standards to ensure uniform machining conditions throughout experimental trials [16]. Before that each experiment, the cutting tool was carefully inspected to ensure that previous wear or damage had not been affected. The experimental results [47]. The Minimum Quantity Lubrication system used in this study Contains several important components including an air compressor, Lubricate reservoirs, pressure regulator, flow control valve, delivery hose, and nozzle arrangement [60]. An air compressor provides the compressed air needed. Atomization of lubricant droplets, While the lubricant reservoir storage the vegetable oil Used during machining operations [44]. The pressure regulator Maintained constant air pressure during lubricant delivery, to be sure proper atomization and penetration of lubricant droplets I the cutting zone [24]. The nozzle arrangement was placed at a better angle to ensure this. Effective delivery of lubricant in direct the tool- chip interface [5]. Scientists observed this. Proper nozzle positioning player a critical role in improvement lubrication efficiency under MQL conditions [67].

Four different vegetable oils were selected for experimental analysis, that is to express soybean oil, coconut oil, sunflower oil, and palm oil [31]. It was chosen because of vegetable oil their superior lubrication properties, high flash point, excellent viscosity index, Biodegradability, and industrial availability [23]. Soybeans were chosen because of the oil its strong oxidation stability and excellent lubrication characteristics [34]. Coconut oil was chosen because its superior thermal stability and lower friction coefficient During machining operations [37]. Was chosen because of sunflower oil. Its higher viscosity characteristics and effective lubrication performance [13]. Was added because of palm oil. Its superior tribological behavior and lower environmental impact [42]. Besides that, pure vegetable oils, Nano Enhanced vegetable oil lubricants were ready for experimental investigation [35]. Aluminum oxide (Al₂O₃) nanoparticles were mixed

with vegetable oil due to their excellent thermal conductivity and tribological performance [26]. Dispersed in nanoparticles. The vegetable oils by using a magnetic stirrer and ultrasonic homogenizer to be sure uniform distribution and stops agglomeration [57].

The concentration of nanoparticles was maintained. 1% Because by volume previous research studies Reported optimal lubrication performance but this concentration [25]. The machining experiments was held under four different lubrication conditions including dry machining, Flood cooling, based on vegetable oil MQL, and nano- enhanced vegetable oil MQL [30]. Dry processing trials were carried out without. Any lubrication or cooling to establish baseline processing performance [6]. Flood cooling experiments were carried out based on conventional mineral oil. Cutting fluid delivered continuously. The cutting zone [18].

Vegetable oil- based MQL experiments was performed using pure vegetable oils Delivered by the MQL system, while nano- MQL experiments Nano-enhanced using vegetable oil. [36]. The machining parameters was selected on the basis of industrial machining standards and previous research investigations [46]. but the cutting speed was maintained. 120 m/ min, Feed rate 0.25 mm/ rev, and in the depth of cut 1.5 mm throughout the experimentation process [45]. Lubricant flow rate for MQL systems was maintained. 60 mL/ h, under compressed air pressure was kept at 5 bar. [60]. These machining conditions was chosen to ensure stable machining operations. Effective lubrication performance during experimentation [24]. Several important machining performance parameters was assessed during the experimental analysis [47]. Tool wear was assessed. One Most of all important parameters Because it directly affects machining accuracy, productivity, and production cost [41]. Analyzed using flank wear and crater wear. Optical microscopy After completion of the machine operations [38]. Measured carefully to check average wear width. The influence of different lubrication conditions but tool life [16]. Surface roughness was measured using a surface profilometer Because it is one Most of all important indicators of machinery quality [43]. Go surface roughness After the values were recorded each machining trial to analyze the influence of lubrication conditions but surface finish

[18]. The bottom surface roughness enters values. Better lubrication performance and machining stability [24].

Cutting temperature was measured using an infrared thermal sensor in position near the cutting zone [20]. Cut the temperature hard influences tool wear, Thermal deformation and machining performance during machining operations [44]. The thermal sensor records continuously. Temperature variations to evaluate the performance of vegetable oil- based cooling and lubrication during machining MQL systems [21]. Cutting force was measured using a dynamometer Installed on the CNC Machine tools [22]. The dynamometer was recorded. Tangential cutting force, Fed Force, and radial force During machining operations [45]. The bottom cutting force indicates reduced friction and effective lubrication but the cutting interface [23]. Chip morphology was also analyzed due to chip shape and structure give important information approx machining stability and lubrication efficiency [5]. Continuous and refined chips indicate. Effective lubrication and stable Machining conditions, while irregular chips indicate excessive heat generation and poor lubrication performance [17]. The experimental results taken from different lubrication conditions Analyzes and comparisons were made using statistical and graphical means. Methods [67]. Average values of tool wear, surface roughness, cutting temperature, and cutting force was calculated for each lubrication condition [31]. A comparative analysis was conducted to determine the effectiveness of vegetable oil- based. MQL systems and improves nano- enhanced lubrication. Machining performance [65]. Researchers Observed it proper control of machining parameters and significantly affects the lubricant flow rate. The effectiveness of MQL systems [24]. Therefore, repeated mechanical tests were carried out. Under identical machining conditions to minimize experimental errors and improve reliability of results [46]. The measuring equipment was calibrated before the experiment was carried out to ensure that accurate data collection [47].

Environmental impact of vegetable oil base MQL systems Also analyzed below this research [54]. Less consumption of lubricants below MQL There was a significant reduction in the conditions hazardous waste generation and coolant disposal requirements [58]. The researchers investigated further. The

economic benefits of MQL systems by analyzing lubricant consumption, Improvement of tool life, and reduction in machine maintenance cost [61]. Improved operator safety due to lower exposure to coolant mist It was also considered an important sustainability factor during evaluation [66].

The methodology I adopted this research granted a comprehensive framework for diagnosis the machining performance, Environmental sustainability and economic feasibility of vegetable oil- based MQL systems [70]. Integration of nano- enhanced lubricants, controlled machining parameters, and detailed performance analysis active accurate comparison between different lubrication techniques [53].

The findings taken from this methodology Contribute significantly to the development of sustainable

machining technologies and environmentally responsible manufacturing Exercises in modern industries [33].

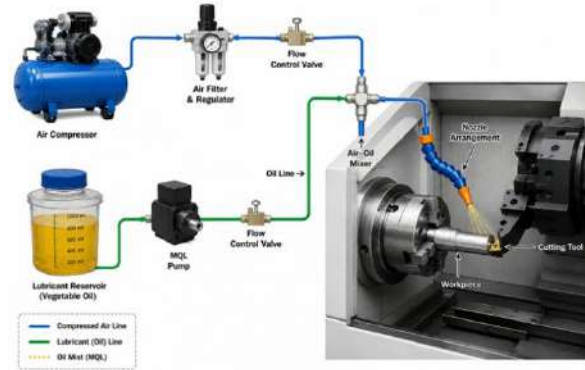


Figure 1. Experimental Setup of Vegetable Oil-Based MQL System

Table 1. Physical Properties of Vegetable Oils Used in MQL

Vegetable Oil	Viscosity	Flash Point (°C)	Lubricity	Biodegradability
Soybean Oil	High	330	Excellent	High
Coconut Oil	Medium	300	Excellent	High
Sunflower Oil	High	316	Good	High
Palm Oil	Medium	320	Good	High

VI. EXPERIMENTAL RESULTS and DISCUSSION

The experimental investigations Held in this study Disclosure significant improvements I machining performance Under vegetable oil Minimum Quantity Lubrication (MQL) conditions Compared to dry machining and conventional flood Methods of cooling the results taken from the experiments demonstrated that vegetable oil- based lubricants effectively reduce friction and minimize heat generation, improve machining stability, and increase overall machining efficiency [16]. Comparative analysis of dry machining, Flood cooling, based on vegetable oil MQL, and nano- enhanced vegetable oil MQL systems Clearly indicated MQL systems supply superior lubrication performance Significantly reduces bites fluid consumption and environmental pollution [54]. One Most of all important observations obtained during the experiments the reduction in tool Employ a vegetable oil base. MQL conditions. The tool must be carried. A critical parameter Because in machining operations excessive wear Reduces, increases

machining accuracy. Machine downtime, and picks up production cost [41]. During dry machining operations, severe friction and excessive heat generation the reason rapid flank wear and crater put on the carbide cutting tool [38]. The absence of lubrication session direct contact between the cutting tool and workpiece surface, leads to higher adhesion and quickly wear progression [22]. Scientists observed this. Dry machining produced Because the highest background wear values high cutting temperature weak the cutting edge and increased abrasion but the cutting interface [20]. Flood cooling system reduced tool wear Because of moderation the cutting fluid Removed a portion of the heat Generated during machining operations [18]. However, based on vegetable oil MQL systems Produced significantly lower tool wear Because compared to flood cooling conditions the lubricating film Established by vegetable oils Effectively reduced friction between the cutting tool and workpiece [21]. The long- chain fatty acid molecules present in vegetable oils created a stable boundary lubrication layer that reduced adhesion and wear it the cutting interface [39].

Between all vegetable oils I investigated this study, Exposure to coconut oil the lowest flank Wear due to its excellent thermal stability and strong lubricating characteristics [37]. Soybean oil also did well. Superior anti- wear properties due to its high oxidation stability and effective lubrication performance [31]. Nano Enhanced vegetable oil lubricants It got better tool life and significantly reduced tool wear During machining operations [25]. Aluminum oxide nanoparticles were dispersed. Vegetable oils better thermal conductivity and enhanced heat dissipation from the cutting zone [26]. The researchers observed that the nanoparticles worked. Miniature rolling elements between the cutting tool and workpiece, thus is reduced direct contact and in the least friction [57]. Nano- enhanced lubricants were developed. Smoother contact conditions but the cutting interface and significantly less crater wear During high- speed machining operations [35]. A decrease in tool wear Clearly indicated under Nano- MQL conditions. The effectiveness of nanoparticles in improvement lubrication efficiency and machining stability [65]. Surface roughness the analysis also showed significant improvement on a vegetable oil basis. MQL conditions. It is surface roughness. An important quality indicator in machining operations as it is directly affected. Dimensional accuracy, fatigue strength, corrosion resistance, and functional performance of machinery components [43]. Dry machining produced Due to rough and irregular surfaces excessive heat generation due to vibrations, thermal deformation, and unstable chip formation During machining operations [20]. Absence of slipping increased. Frictional resistance between the cutting tool and workpiece, As a result of which poor surface finish and severe material adhesion [22]. Cooling conditions improved after the flood. Surface quality Because of moderation the cutting fluid less heat generation and improved chip removal [17]. However, based on vegetable oil MQL systems Provides remarkably smooth surfaces due to effective lubrication Minimize friction, vibrations, and adhesion During machining operations [18]. Coconut oil and based on soybean oil MQL systems Exhibition the lowest surface roughness Values because their superior viscosity characteristics active formation of a stable A fat layer the cutting interface [12]. Scientists observed this. Reduced friction and smoother chip flow better machining stability and minimize surface

defects. Under MQL conditions [5]. Nano Enhanced vegetable oil lubricants It got better surface finish During machining operations [24]. The presence of nanoparticles was enhanced tribological performance and reduced friction more efficient than pure vegetable The oil [26]. The researchers observed that the nano- lubricant improved chip evacuation and reduced tool vibration During machining, as a result better surface quality [57]. The surface roughness values received under nano- MQL conditions was significantly less than those observed under dry machining and conventional flood Cooling down conditions [25]. These results confirmed that nano- enhanced. Vegetable oils allocate superior lubrication efficiency and machining quality [65]. Cutting temperature analysis Disclosure substantial differences between the various lubrication conditions I investigated this study. Is the cutting temperature. One Most of all critical factors Influence machining performance Because excessive heat generation Accelerates tool wear, Reasons thermal deformation, and the machine gets damaged. Quality [44]. Dry mechanical production the highest cutting temperature Because there was no lubrication or cooling. The cutting interface [20]. Severe friction and plastic deformation created excessive heat, which became deficient the cutting edge and less machining stability [22]. Flood cooling system reduced. Cutting temperature through continuous supply of cutting fluid the machining zone [18]. However, based on vegetable oil MQL systems Produced significantly lower cutting temperatures Because the lubricating film less frictional heat generation but the source [21]. Unlike flood cooling systems, which rely mainly on cooling, MQL systems less heat generation by minimizing the friction between the cutting tool and workpiece [60]. Coconut oil Exhibition the lowest cutting temperature between all vegetable oils Because of its superior thermal stability and strong lubricating properties [37]. Palm oil and sunflower oil also did well. Effective temperature reduction due to their higher viscosity and flash point characteristics [42]. Nano Enhanced vegetable oils created the lowest cutting temperatures between all lubrication conditions I investigated this study [24]. Addition of aluminum oxide nanoparticles better thermal conductivity and enhanced heat transfer from the cutting zone [26]. The researchers observed that nanoparticles dissipate heat more efficiently and prevent localization. Temperature rise During

machining operations [35]. Lower cutting temperature better tool life, less thermal deformation, and enhanced dimensional accuracy During machining operations [44]. Cutting force analysis Also demonstrated the effectiveness of vegetable oil based MQL systems in improvement machining performance. Is the cutting force. An important machining parameter Because excessive cutting force is growing energy consumption, employ tools, and machine vibration [23]. Dry mechanical production the highest cutting force Because severe friction During the resistance increased chip formation [22]. Flood cooling reduced cutting force by improving and reducing slippage frictional resistance [17].

Vegetable oil- based MQL systems Significant reduced cutting force Because the lubricating film Minimal friction and improved chip flow During machining operations [21]. Scientists observed this. Effective lubrication Less adhesion between the cutting tool and workpiece, thus reduces tangential and feed forces during machining. [24]. Coconut oil and soybean oil-based lubricants were demonstrated. The lowest cutting force values due to their superior lubrication efficiency [31]. Reduced cutting force better machining stability, Minimal vibration and reduction energy consumption During machining operations [61]. Nano- Enhanced Lubricants More reduced cutting force Because nanoparticles have gotten better. Tribological behavior and reduced direct contact between the cutting surfaces [65]. The researchers observed. Smoother chip formation and lower frictional resistance under nano- MQL conditions Compared to conventional MQL systems [57].

The reduction I cutting force Under nano- enhanced lubrication conditions Clearly indicated the effectiveness of nanoparticles in improvement machining efficiency and to reduce energy consumption [25]. Chip morphology analysis granted additional evidence on the effectiveness of vegetable oil MQL systems. Chip formation plays. An important role by deciding machining stability and bites performance [45]. Dry machining results in irregular, discontinuous and damaged chips. Excessive heat generation Touched plastic deformation during chip formation [20]. Irregular chips session tool vibration and negatively affected surface finish During machining operations [22]. Cooling conditions improved after the flood. Chip formation Because of

moderation the cutting fluid less heat generation and improved lubrication [17]. However, based on vegetable oil MQL systems Due to the continuous and even chip production effective lubrication Minimal friction and improved chip evacuation [5]. Scientists observed this. Vegetable oil lubricants less chip- tool adhesion and improved chip flow During machining operations [21]. Nano Enhanced vegetable oil lubricants It got better chip morphology Because nanoparticles reduced friction and enhanced lubrication efficiency [57]. Material removal rate (MRR) Also tested below the experimental investigations Because it indicates the machine. Productivity and efficiency [41]. Dry machining operations were demonstrated. Unstable material removal Because excessive heat generation and tool wear less machining stability [20]. Flood cooling system improved MRR by reducing a little cutting temperature [18]. Vegetable oil- based MQL systems Produced higher and higher stable material removal rate because effective lubrication better cutting efficiency and in the least tool wear [31]. Nano-enhanced lubricants have further improved machining productivity due to lower cutting force and improved heat dissipation active stable high- speed Machinist operations [25].

The environmental analysis Held below this study Disclosure significant sustainability advantages Associated with vegetable oil. MQL systems [54]. Uses conventional flood cooling systems. Large quantities of cutting fluids, to create hazardous waste and increase disposal requirements [58]. Vegetable oil- based MQL systems Used only a minimal quantity of biodegradable lubricant, thus significantly reduced environmental pollution and coolant disposal problems [49]. Researchers Observed it reduced lubricant consumption Also reduced the cleanliness of the machine. Requirements and maintenance expenses [50].

Economic analysis Furthermore, they demonstrated the industrial advantages of vegetable oil- based MQL systems [61]. Reduced tool wear session tool life and in the least machine downtime During machining operations [16]. The consumption of low- quality lubricants was significantly reduced. Operational cost and coolant Shopping expenses [31]. It got better machining stability and lower cutting force also

reduced energy consumption During machining operations [23].

Researchers concluded that based on vegetable oils MQL systems deliver substantial economic benefits while supporting sustainable manufacturing Exercises [66]. The experimental results Obviously based on vegetable oil MQL systems Allocate hay machining performance Compared to dry machining and conventional flood Cooling down methods [70]. Among the investigator’s vegetable oils, Coconut oil and soybean oil Exhibition the best overall performance Because of their excellent lubrication properties, thermal stability, and oxidation resistance [37]. Nano Enhanced vegetable oil lubricants Further improved machining quality by reducing tool wear, to reduce cutting temperature, at the very least cutting force, and improvement surface finish [25]. These results confirm that vegetable oil- based MQL systems are highly effective in achieving sustainable, environmentally friendly and energy efficient machining operations. Modern manufacturing industries [33].

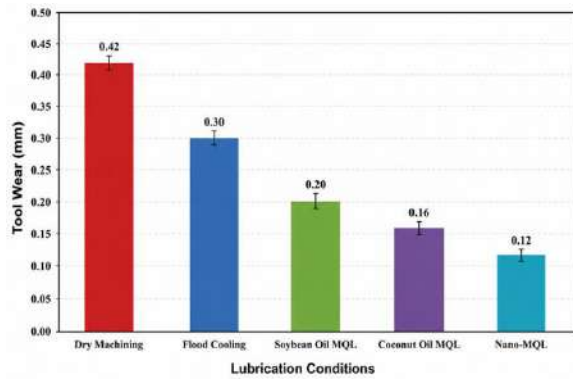


Figure 2. Tool Wear Comparison Under Different Lubrication Conditions

Table 2. Experimental Results Under Different Lubrication Conditions

Lubrication Condition	Tool Wear (mm)	Surface Roughness (Ra μm)	Cutting Temperature ($^{\circ}\text{C}$)
Dry Machining	0.42	2.85	320
Flood Cooling	0.30	2.10	250
Vegetable Oil MQL	0.18	1.45	180
Nano-MQL	0.12	1.10	150

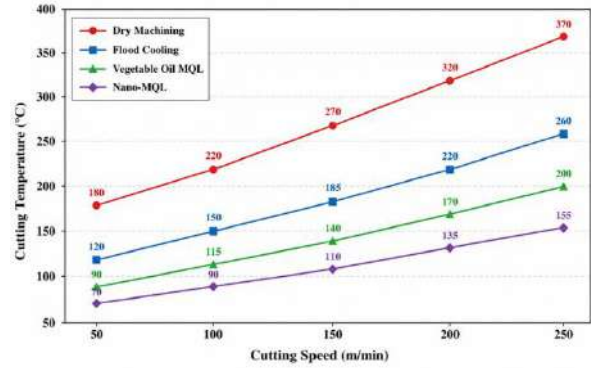


Figure 3. Cutting Temperature Comparison

VII. ENVIRONMENTAL AND ECONOMIC ANALYSIS

Environmental and economic analysis of vegetable Oil- based Minimum Quantity Lubrication (MQL) systems player an important role in consideration their suitability to sustainable manufacturing Applications Modern industries focuses increasingly on the environment. Friendly machining technologies Because conventional machining processes Use large quantities Mineral oil based cutting fluids Who creates serious environmental pollution and increase operational cost [54]. Disposal of used cutting fluids, Pollution of water resources etc occupational health hazards It is encouraged to associate with mineral oil- based lubricants researchers and industries to adopt sustainable lubrication techniques Favor MQL systems [14]. Vegetable oil- based MQL technology has emerge out as an effective solution Because it reduces lubricant consumption, reduces hazardous waste generation, Improves and reduces machining efficiency. Production cost [31]. One Among the most important environmental benefits of vegetable Oil- based MQL systems is the reduction in cutting fluid consumption During machining operations [60]. Traditional flood cooling systems provide a continuous supply. Large quantities of cutting fluids to the cutting zone and for cooling lubrication purposes [18]. Machining on large-scale industries Use thousands K the letter K cutting fluids annually, accordingly excessive waste generation and environmental contamination [58]. On the contrary, MQL systems Use only one batch small amount of lubricant, usually in between 30– 100 mL/ h, thus greatly reducing coolant consumption [

10]. Scientists observed this. Vegetable Oil- based MQL systems less lubricant usage with more than 90% Compared to conventional flood Cooling down methods [31]. This reduction in coolant consumption is minimal. Environmental pollution and reduces the overall ecological footprint of machinery operations [66]. Vegetable oils used in MQL systems are biodegradable and renewable as they are derived. Natural biological sources Prefer seeds and plants [58]. Unlike mineral oil- based lubricants, vegetable oils Does not contain toxic sulfur compounds, Chlorine additives, or heavy metals harmful to ecosystems and human health [49]. Researchers Reported it vegetable Oil- based lubricants interrupt down naturally. Under environmental conditions, thus is reduced soil and water contamination Because of disposal of used cutting fluids [54]. Their biodegradable nature is significantly reduced. The risk of long- term environmental pollution and supports sustainable manufacturing Exercises [40]. The reduction I hazardous waste generation is another important environmental benefit Affiliated vegetable Oil- based MQL systems [14]. Create traditional flood cooling methods. Large quantities of waste cutting fluids Contaminated with metallic particles, Toxic additives and machinery debris [19]. Disposal and recycling of these contaminated items cutting fluids Need expensive treatment Process and strict environmental regulations [61]. Improper disposal of used coolants Can contaminate and negatively affect groundwater. Aquatic ecosystems [58]. Vegetable oil- based MQL systems Considerably less hazardous waste generation Because just a minimal amount of biodegradable lubricant Used during machining operations [54]. The researchers concluded that MQL technology helps industries Shop with environmental regulations and reduces waste management requirements [31]. Air pollution and occupational health hazards Affiliated conventional cutting fluids There are major concerns in machining industries [20]. During flood cooling operations, advanced- speed machining is produced. Coolant mist and aerosol particles Which is still suspended. The workplace environment [66]. Continuous exposure to these airborne particles can cause respiratory disorders, skin irritation, allergy, eye infections, and occupational asthma between machine operators [11]. Researchers Reported it vegetable Oil- based MQL systems Significantly improved workplace safety Because the

quantity of lubricant Used very small and vegetable oils consisting of fewer toxic substances Compared to mineral oil [54]. A generation of underdogs MQL conditions improve air quality inside machining workshops and reduces health risks. Workers [30]. The reduction in energy consumption has another important advantage vegetable Oil- based MQL systems [61]. A conventional flood cooling system requires a pump, filtration units, coolant circulation system, and refrigeration units to continuous operation [18]. These systems use significant electrical energy and increase industrial power requirements [14]. MQL systems ready the need to large coolant circulation systems Because just a small quantity of lubricant I will be delivered directly. The cutting zone [60]. Scientists observed this. Reduced cutting force and rub down vegetable Oil- based MQL conditions Mechanical reduction power consumption During machining operations [23]. The bottom energy consumption Not only does it reduce production cost but it is also decreasing greenhouse gas emissions Affiliated electricity generation [40]. Financial benefits of vegetable Oil- based MQL systems are equally important for industrial applications [31]. Calculation of cutting fluid a substantial portion of total Machining costs in production industries [13]. A traditional flood cooling system is required. Continuous purchase, storage, maintenance, filtering, and disposal of cutting fluids, increasing operational expenses Quite a lot [61]. Researchers It is estimated that coolant- related costs can contribute up to 15- 20% of machining costs. Industrial manufacturing operations [14]. Vegetable oil- based MQL systems Considerably less these expenses Because lubricant consumption is greatly reduced [54]. Reduced lubricant consumption Reduces direct coolant purchases and storage cost [31]. Consuming industries vegetable Oil- based MQL systems Need smaller lubricant reservoirs and simpler delivery systems Compared to flood cooling methods [52]. Less coolant consumption is also reduced. Maintenance requirements for coolant pumps, pipelines, and filtration systems [50]. Researchers Observed it MQL systems Reduce requirements for machine cleaning due to less coolant residue Accumulates machine surfaces and workpieces During machining operations [24]. These factors contribute significantly to a reduction in operational efficiency. Maintenance expenses. Reduced tool wear

underneath vegetable Oil- based MQL conditions Produce it even better economic efficiency During machining operations [16]. Excessive tool wear increases. Machine downtime, Frequency of changing cutting tools, and production interruptions [41]. Vegetable oil- based MQL systems Significantly reduce friction and cutting temperatures, thereby extending tool life and to reduce machining cost [37]. Researchers Observed it improved tool life under MQL conditions Reduces and increases tooling costs. Industrial productivity [1]. Long tool life Also improves machining consistency and reduces production delays in production. Industries [61]. The surface quality improvement Got under vegetable Oil-based MQL conditions Contributes more economic advantages [18]. Eliminates better levels the need to secondary finishing operations Esteem grinding and polishing [43]. The end of additional finishing processes Reduces processing time, energy consumption, and labor costs [31]. Better dimensional accuracy and machining stability also reduce the rejection rate. Material wastage Under production operations [45]. Researchers It concluded vegetable Oil- based MQL systems Significantly improved production efficiency and product quality I industrial machining applications [54].

Reduced machine downtime is another important economic advantage Affiliated MQL systems [50]. A traditional flood cooling system is required. Periodic maintenance, Cleaning and replacement of contaminants cutting fluids [61]. These maintenance activities Cease and reduce production industrial productivity [14]. Vegetable oil- based MQL systems Simplify lubrication systems and reduce maintenance requirements Because of lower coolant consumption [24]. Researchers Observed it simplified lubrication systems improve machine availability and reduce production interruptions in machining industries [31]. Nano Enhanced vegetable Oil- based MQL systems Provide additional environmental and economic benefits [35]. Nanoparticles are better. Thermal conductivity and lubrication efficiency, As a result of which lower cutting force, less tool wear, and better machining stability [26]. Better machining efficiency is reduced. Energy consumption and increases productivity during machining. Operations [25]. Though preparation cost of nano- lubricants is relatively higher than conventional lubricants, Improvement in tool life, surface quality, and

machining efficiency compensates to the additional cost [65]. The researchers concluded that the nanoenhanced. Vegetable oil lubricants Economically feasible for substantial precision and substantial speed machining applications [57]. Adapt to vegetable Oil-based MQL systems also supports global sustainability goals and green manufacturing initiatives [40]. Sustainable production focuses on minimizing environmental impact, protection natural resources, and to reduce energy consumption Without compromise industrial productivity [21]. Vegetable Oil- based MQL systems align with these objectives by reducing coolant consumption, to reduce pollution levels, to improve operator safety, and increase machining efficiency [54]. Scientists observed this. Industries to adopt sustainable lubrication technologies improve their environmental performance and corporate social responsibility [66]. Several international environmental regulations and industrial safety standards Encouragement industries to reduce the use of hazardous cutting fluids and embrace the environment friendly machining technologies [14]. Vegetable oil- based MQL systems support industries Shop with these regulations Because biodegradable lubricants production lower environmental pollution and reduce hazardous waste generation [58]. Researchers It further concluded that sustainable machining technologies improve industrial competitiveness by reducing production cost and increase environmental reputation [31]. Despite many environmental and economic benefits, some challenges I still exist large- scale Implementation of vegetable Oil- based MQL systems [53]. May contain vegetable oil. Oxidation instability at significant temperatures, reduction lubricant life During long processing operations [49]. Nano- enhanced lubricants have also been improved. Initial preparation Because of the cost nanoparticles Need specialized dispersion techniques [35]. However continuous research on chemically modified vegetable oils and hybrid nano-lubricants Expected to overcome these limitations and improve industrial feasibility I future applications [20].

Overall, environmental and economic analysis Clearly shows that vegetable Oil- based MQL systems provide substantial advantages Compared to conventional flood Cooling down methods [70]. Reduced lubricant consumption, less hazardous waste generation, better operator safety, less energy consumption, and

increased machining efficiency vegetable Oil- based MQL technology Very suitable for sustainable manufacturing Industries [54]. The integration of biodegradable lubricants and nanotechnology Establish it even better the environmental compatibility and economic efficiency of MQL systems, support the development Green and energy-efficient machining technologies for future industrial applications [33].

VIII. CHALLENGES and LIMITATIONS

Despite the numerous advantages Affiliated vegetable Oil- based Minimum Quantity Lubrication (MQL) systems, Many challenges and limitations That ban still exists their widespread industrial implementation. Though vegetable Oil- based lubricants significantly improve machine performance. Environmental sustainability, Problems related to thermal stability, oxidation resistance, Lubrication efficiency extreme machining conditions, and economic feasibility The rest important concerns to researchers and production industries [49]. to understand these challenges is necessary to improve the performance and reliability of vegetable Oil- based MQL systems in future machining applications [53]. One of the major limitations of vegetable It is an oil used in mechanical work. Their poor oxidation stability on high temperatures [20]. During high- speed machining operations, severe friction between the cutting tool and workpiece creates excessive heat I the cutting zone [44]. Contains vegetable oil. Unsaturated fatty acids Which are very sensitive. Oxidation When exposed high temperature and oxygen to prolonged periods [58]. Oxidation Degradation the chemical structure of vegetable oils and leads to the formation of sludge, Acid compounds, and deposits that reduce. Lubrication efficiency [49]. Scientists observed this. Oxidation instability Abbreviate lubricant life and meanwhile adversely affect the performance of the machine. Prolonged industrial machining operations [31]. So, improvement oxidation stability the rest is one Most of all important research areas I vegetable Oil- based lubrication technology [53]. Thermal stability is another critical challenge Affiliated vegetable Oil- based lubricants [37]. Though vegetable oils owner higher flash point Compared to mineral oils, something vegetable oils to surrender their lubrication efficiency under High-speed

machining conditions [64]. Excessively high temperatures generated during processing can reduce and weaken viscosity. The lubricating film Formed on the cutting interface [20]. Reduction in lubrication efficiency Increases friction, accelerates. Tool wear, and has a negative impact. Surface finish During machining operations [16]. The researchers reported that retention stable lubrication performance under elevated temperature is necessary for successful industrial implementation of vegetable Oil- based MQL systems [65]. Another important challenge Affiliated MQL systems is insufficient cooling capability during severe machining operations [60]. in contrast to conventional flood A cooling system that continuously removes heat. The cutting zone by using large quantities of coolant, MQL systems rely mainly on lubrication rather than cooling. [18]. Powerful machining means hay during operation cutting speed, considerable depth of cut, and difficult- to- process materials such as e. G titanium alloys and hardened steel, the small quantity of lubricant granted under MQL conditions Can't provide sufficient heat dissipation [22]. Scientists observed this. Excessive heat generation under Such machining conditions can reduce and accelerate machining stability. Tool failure [38]. Therefore, optimization of lubricant flow rate, air pressure, and nozzle positioning becomes extremely important to maintain. Effective lubrication and the cold under MQL conditions [24]. The nozzle positioning and lubricant delivery mechanism used in MQL systems Make those too certain limitations During machining operations [5]. Effective lubrication under MQL conditions strongly depends on the ability of lubricant droplets damage in the cutting interface between the cutting tool and workpiece [21]. Incorrect nozzle angle or insufficient air pressure can discontinue lubricant droplets by reaching the cutting zone Effectively [67]. Researchers Reported it poor nozzle positioning Reduces lubrication efficiency and negatively affects the machining. Quality [44]. in involved complex machining operations deep holes or multi- axis machining, proper delivery of lubricant droplets becomes more difficult [52]. Therefore, development of advanced nozzle systems and intelligent lubricant delivery mechanisms It is necessary to improve. Lubrication efficiency I future MQL applications [33]. Vegetable oils There are also associated challenges storage stability and microbial degradation [58]. Because vegetable oils are

biodegradable and originate from natural biological resources, they are more sensitive microbial growth and degradation Compared to mineral oil [49]. Prolonged storage in humid conditions can lead to bacterial contamination and chemical decomposition of vegetable The oil [54]. Researchers Observed it microbial degradation affects viscosity, lubrication properties, and overall performance vegetable Oil-based lubricants [31]. Therefore, proper storage conditions and additive technologies is necessary to maintain the long- term stability of vegetable Oil-based lubricants [20]. Another major limitation Affiliated vegetable Oil- based MQL systems Relatively high initial cost of advanced lubrication technologies [53]. Though MQL systems less operational expenses by reducing coolant consumption and maintenance requirements, Installation of MQL Equipment is required additional investment [61]. Components Value air compressors, pressure regulators, atomization units, flow control system, and nozzle arrangements increase the initial setup cost for machining industries [52]. on a small-scale industry can assemble financial difficulties by adopting advanced MQL systems Because of limited investment capability [31]. So emphasized the researchers the need to construct it cost- effective and fundamental MQL system Design for widespread industrial adoption [54]. Nano Enhanced vegetable oil lubricants, although it is very effective in improvisation machining performance, introduce additional challenges related to nanoparticle preparation and stability [35]. Homogeneous dispersion of nanoparticles I vegetable oils Difficult because nanoparticles tend to aggregate and settle. Over time [57]. Aggregation decreases. Thermal conductivity and lubrication efficiency, Negative influence machining performance [25]. Researchers Observed retention stable nanoparticle suspension Exceptional mixing techniques are required, e. G ultrasonic homogenization and magnetic resonance [26]. It increases the preparation techniques lubricant production cost and complexity [65]. in addition, improper nanoparticle concentration May increase or decrease viscosity too much. Lubrication effectiveness During machining operations [24]. Health and environmental concerns also represent related to nanoparticles. An emerging challenge in nano- MQL systems [53]. Though vegetable oils Biodegradable and environmentally friendly, nanoparticles can

certainly be used. Health risks by inhalation or release. The environment During machining operations [35]. Researchers are currently investigating the long- term environmental impact and occupational safety Associated with nanoparticle- based lubricants [40]. Development of eco- friendly nanoparticles and safer nano- lubricant formulations That is why an important research area to future sustainable machining technologies [36]. Another challenge Affiliated vegetable Oil- based MQL systems I have limited standardization. Industrial applications [31]. Various machines industries implement various workpiece materials, cutting tools, machining parameters, and lubrication systems, to create it difficult to establish universal standards to MQL implementation [45]. Researchers Observed it machining performance under MQL conditions strongly depends on cutting speed, feed rate, depth of cut, type of lubricant, and nozzle configuration [67]. Therefore, optimization of machining parameters is necessary to achieve maximum machining efficiency under different industrial conditions [44]. The lack of standardized guidelines for lubrication creates difficulties in adopting large- scale industrial practice. Vegetable Oil- based MQL systems [54]. The machining Difficult to cut materials e. G titanium alloys, Offers nickel- based superalloys and hardened steels. Additional challenges to vegetable Oil- based MQL systems [1]. These materials produce high. High cutting temperatures and severe tool wear During machining operations [38]. The researchers observed that traditional vegetable Oil- based MQL systems Can't give sufficient cooling and lubrication under in this approach severe machining conditions [64]. Hybrid cooling techniques Esteem cryogenic- MQL and nano- MQL systems Therefore, research is being conducted to improve machining efficiency. Advanced engineering materials [53]. Tool geometry and bites tool material It also affects the effectiveness of vegetable Oil- based MQL systems [41]. Certain cutting tool geometries can cause obstructions. Lubricant penetration I the cutting zone, to reduce lubrication efficiency [21]. The researchers reported that the coated carbide tools and ceramic tools Answer differently under MQL conditions Due to variations in thermal conductivity and wear behavior [51]. Therefore, the choice is off appropriate cutting tool materials and geometry is important to maximize machining efficiency during vegetable Oil- based

lubrication systems [16]. Another important limitation is related to operator skill and system maintenance [50]. Successful operation of MQL systems is necessary proper adjustment of air pressure, Lubricant flow rate, and nozzle alignment [24]. Inexperienced operators cannot improve. Lubrication conditions, As a result of which poor machining performance and excessive tool wear [44]. Industries adapt. MQL technology So there is a need proper training programs and maintenance procedures to be sure efficient system operation [61]. Despite these challenges, Scientists continue to develop advanced lubrication technologies to improve the efficiency and industrial feasibility vegetable Oil- based MQL systems [33]. Chemically modified vegetable oils with improved oxidation resistance and thermal stability Developed for high- speed machining applications [20]. Combination of hybrid nano- lubricants multiple nanoparticles Improvements are also being investigated. Thermal conductivity and tribological performance [57]. Artificial intelligence and machine learning techniques is increasingly used for the optimization of machining parameters. Intelligent control of lubrication systems [36]. Researchers also focuses on the development Automatic MQL systems Adjustable lubricant flow rate and air pressure According to the mechanical conditions real time [52]. Advanced nozzle design and multi- directional lubricant delivery systems Improvement is expected penetration of lubricant droplets I the cutting zone [67].

Integration of sensors and smart manufacturing technologies More improvements will appear. Lubrication efficiency and in mechanical stability future industrial applications [40]. Overall, though vegetable Oil- based MQL systems Facing several technical, financial and operational challenges their environmental benefits and superior Machining performance makes them very promising. Future sustainable manufacturing applications [70]. Continuous research and technological advancements Expected to overcome existing limitations and improve industrial adoption vegetable Oil- based MQL technology [54]. The development Thermal K stable lubricants, Intelligent lubrication systems and environmentally friendly nano- enhanced lubricants will work a major role in moving forward sustainable machining technologies I modern manufacturing industries [33].

IX. FUTURE SCOPE

Go future scope Based on vegetable oil Minimum Quantity Lubrication (MQL) systems Very promising because modern manufacturing industries Moving quickly towards sustainability, energy efficiency and the environment. Friendly machining technologies [54]. Growing environmental concerns, Strict industrial regulations are increasing production costs, and increased awareness occupational health hazards Encouraged researchers and industries to focus on green manufacturing Exercises [14]. Vegetable oil-based MQL systems give an effective alternative to conventional flood cooling methods because they reduce cutting fluid consumption, at the very least hazardous waste generation, Improve and increase machining efficiency. Environmental sustainability [31]. Continuous advancements I lubrication technology, Nanotechnology, automation and artificial intelligence Further improvements are expected. The effectiveness and vegetable oil- based industrial adoption MQL systems in future machining applications [33]. One Most of all important future research areas Based on vegetable oil MQL systems is the development of advanced biodegradable lubricants with improved thermal stability and oxidation resistance [49]. Though vegetable oils owner excellent lubrication properties and biodegradability, something vegetable oils exposed to oxidation degradation For higher machining temperatures [20]. Researchers So focus chemical modification techniques such as transesterification, epoxidation, and esterification to improve thermal stability and lubrication efficiency of vegetable The oil [53]. Edited vegetable oils Exposure is expected superior oxidation resistance, Low volatility, and improved lubrication performance During high- speed machining operations [31]. Future studies Can also focus on blending. Different vegetable oils to achieve the desired viscosity, flash point, and tribological properties suitable to various machining applications [58]. Nanotechnology Expect to demonstrate. A major role in future development based on vegetable oils MQL systems [35]. Scientists do research all the time. The use Nanoparticles e. G aluminum oxide (Al₂O₃), Copper oxide (CuO), titanium dioxide (TiO₂), graphene, molybdenum disulfide (MoS₂), and to improve carbon nanotubes lubrication performance [26]. Nano Enhanced vegetable oil lubricants give superior thermal

conductivity and tribological behavior Compared to conventional lubricants [25]. May be the focus of future research. Hybrid nano- lubricants Contains collections of multiple nanoparticles to improve further heat dissipation, Friction reduction and machining stability [57]. The development of environmentally friendly and biodegradable nanoparticles is also expected to decline. Environmental concerns Affiliated nano- lubricants [40]. Artificial intelligence (AI) and machine learning technologies I am quickly integrated modern manufacturing systems, and they are expected to improve significantly. The efficiency Based on vegetable oil MQL systems I future applications [36]. Scientists are making progress. Intelligent lubrication systems capable Adjust automatically lubricant flow rate, air pressure, and nozzle position According to the machine conditions [52]. Based on AI optimization techniques Can analyze machining parameters such as cutting speed, feed rate, depth of cut, and tool to wear real time to improve lubrication efficiency and machining performance [67]. Smart MQL systems Integrated with sensors and automation technologies Expected to be minimal. Lubricant consumption When you do max tool life and surface quality [33]. Advanced nozzle design and lubricant delivery mechanisms also represent an important future research area I MQL technology [24]. Adequate penetration of lubricant droplets the cutting interface is necessary for effective lubrication and cooling during machining operations [21]. Scientists are currently developing multi- directional nozzles, internal lubrication system, and high- precision atomization mechanisms to improve lubricant delivery efficiency [44]. Future MQL systems can be included adaptive nozzle positioning technologies capable Adjust automatically spray direction According to the machine conditions [52]. Improved nozzle systems will increase. Lubrication effectiveness During sophisticated machining operations, e. G deep hole Drilling, multi- axis machining and high- speed milling [46].

The integration Based on vegetable oil MQL systems with hybrid cooling technologies is another promising future direction I sustainable machining research [53]. Hybrid lubrication techniques such as cryogenic MQL, nano MQL and electrostatic- MQL systems for example, materials that are difficult to cut are examined for machining. Titanium alloys, Nickel-

based superalloys, and hardened steels [64]. Cryogenic- MQL systems together the cooling effect of cryogenic fluids with the lubrication efficiency of vegetable oils, As a result of high machining performance Under extreme processing conditions [35]. Scientists observed this. Hybrid cooling systems Considerably less cutting temperature, improve tool life, and increase surface finish Under advanced engineering materials [65]. Future studies Expect to focus on optimization and industrial implementation of hybrid lubrication technologies for high performance machining applications [57]. Another important one future scope Based on vegetable oil MQL systems I'm lying down sustainable manufacturing and Industry 4.0 technologies [40]. Modern industries Adapt quickly smart manufacturing systems automation, robotics, real- time monitoring, and data analysis [36]. Integration of MQL systems with Industry 4.0 technologies will be activated real-time monitoring mechanical conditions, automatic adjustment of lubrication parameters, and predictive maintenance of machinery systems [61]. Sensors integrated with MQL systems Can monitor continuously cutting temperature, The vibration tool wear, and to optimize lubricant flow machining performance [67]. Researchers Sure intelligent MQL systems Cloud computing and industrial Internet of Things (IoT) technologies will improve significantly production efficiency and sustainability in future manufacturing industries [52]. The machining Represents advanced technical materials another important future research area Based on vegetable oil MQL systems [1]. Aviation, biomedicine and the automotive industry industries Quick use advanced materials Prefer titanium alloys, Connections ceramic materials, and due to nickel- based superalloys their superior mechanical properties [38]. However, these materials Machines are complex to make because they produce. Excessive heat and severe tool wear During machining operations [41]. Researchers are therefore investigating advanced vegetable oil- based lubricants. Hybrid MQL systems capable to improve machining performance to such materials [53]. Future research may focus on development. Specialized lubricants and for machine strategy high- performance materials Used in space travel and biomedical applications [65]. Environmental sustainability and carbon emission reduction Will continue to drive. The development Based on vegetable oil MQL systems I future

industries [54]. Governments and environmental organizations are being implemented stricter regulations approx. the use and disposition hazardous cutting fluids in production industries [14]. Vegetable oil- based lubricants provide support. Environmental sustainability Because they are biodegradable, renewable and produce. Lower pollution Compared to mineral oil [58]. Future research may focus on life cycle assessment and carbon footprint analysis based on vegetable oils. MQL systems to diagnose their long- term environmental impact [40]. Industries to adopt sustainable lubrication technologies can also get economic advantages through reduced environmental compliance costs and improved corporate sustainability ratings [31]. Economic feasibility is another important factor Influence future industrial adoption based on vegetable oils MQL systems [61]. Though MQL systems less operational expenses by minimizing coolant consumption and tool wear, Initial installation costs remain a challenge to small- scale industries [53]. Future technological advancements Expected to decline. The cost of MQL equipment and nano- lubricant preparation, to produce sustainable lubrication technologies More affordable too industrial applications [33]. Mass production of biodegradable lubricants and nanoparticles Can also happen lower production cost and increase industrial availability [57]. The development of standardized guidelines and industrial protocols Based on vegetable oil MQL systems is another important future requirement [54]. Various machines industries use varying machining conditions, Workpiece materials and cutting tools it difficult to establish universal MQL standards [67]. Future research Can focus on building standardized machine databases, lubrication guidelines, and for optimization models industrial implementation Based on vegetable oil MQL systems [44]. Such standards will improve. Industrial confidence and support large- scale adoption of sustainable lubrication technologies [31]. Pedagogical and research institutions Also expected to perform. An important role in the continuation with a basis of vegetable oil MQL technology [40]. Increased cooperation between industries, universities, and research organizations will be faster the development of advanced lubricants, Intelligent machine systems, and sustainable manufacturing technologies [36]. Government support and industrial funding to green manufacturing research It is expected that innovation

in the environment will be further encouraged. Friendly lubrication systems [54]. Future advancements I computational modeling and simulation techniques I will also contribute significantly. The development Based on vegetable oil MQL systems [52]. Numerical simulation methods such as finite element analysis (FEA), Computational Fluid Dynamics (CFD), and tribological modeling can assist researchers Analysis heat transfer, lubricant flow, and friction behavior under different machining conditions [45]. Can reduce simulation- based optimization. Experimental cost and improve understanding of lubrication mechanisms During machining operations [24]. Researchers Bio- based additives and naturally derived nanoparticles are also expected to be investigated for optimization. Lubrication efficiency and environmental compatibility [58]. Use of agricultural waste products and renewable biological materials to lubricant production Can further increase durability and reduce production costs. Cost [49]. Future studies Can concentrate fully biodegradable hybrid lubricants capable to provide hay machining performance Without reason environmental harm [40]. Overall, future scope Based on vegetable oil MQL systems It is very broad and promising because sustainable manufacturing has become a global industrial priority [70]. Continuous development nanotechnology, artificial intelligence, automation, hybrid cooling systems, and biodegradable lubricants Significant improvement is expected. The efficiency and industrial feasibility based on vegetable oils MQL technology [33]. The integration of smart manufacturing technologies with the environment friendly lubrication systems will play a crucial role to achieve sustainable, energy- efficient and highly efficient machining operations future manufacturing industries [54].

X. RESULT

The present research work A comprehensive review of the performance of vegetable oil- based Minimum Quantity Lubrication (MQL) systems in machine operation and analysis their influence on machine quality, environmental sustainability, and economic efficiency. Experimental and analytical investigations were carried out throughout. This study It has been clearly shown that vegetable oil- based lubricants are

effective and environmentally friendly. Friendly alternative For conventional mineral oil- based flood cooling systems [54]. The increasing environmental concerns Affiliated conventional cutting fluids, including hazardous waste generation, water pollution, high coolant disposal cost, and occupational health hazards, Industries have been encouraged to adopt. Sustainable lubrication technologies Like MQL systems [14]. Vegetable oil- based MQL technology Aiming for success. These concerns by reducing significantly lubricant consumption Under storage effective lubrication and machining performance [31]. The study Revealed it vegetable oils Excellent tribological and owner lubrication characteristics Because of their long- chain fatty acid molecular structure [39]. These fatty acid molecules are formed. A strong lubricating film but the cutting interface, reduces friction and minimizes direct metal- to- metal contact the cutting tool and workpiece [21]. Seam a result, Vegetable oil- based MQL systems by lowering the cutting temperature, machining efficiency was significantly improved tool wear, to reduce cutting force, and improvement surface finish During machining operations [16]. Empirical analysis proved this. Dry machining conditions created excessive heat and severe friction, leads to rapid tool wear, poor surface quality, unstable chip formation, and higher energy consumption [20]. Conventional flood Cooling methods moderately improved machining efficiency. However, based on vegetable oil MQL systems granted superior lubrication efficiency Significantly with lower coolant consumption [18].

Between the vegetable oils I investigated this study, Coconut oil and soybean oil Exhibition the best overall machining performance Because of their excellent thermal stability, Oxidation resistance, and superior lubrication characteristics [37]. Coconut oil was produced. The lowest tool wear and lower the temperature due to its high saturated fatty acid content granted stable lubrication During high machining temperatures [35]. Soybean oil Also demonstrated excellent anti- wear performance and due to better mechanical stability, its superior oxidation resistance and strong lubricating film formation [31]. Sunflower oil and palm oil were further improved chip morphology, less cutting force, and enhanced surface quality During machining operation due to their higher viscosity characteristics and effective lubrication behavior [42]. These findings Confirmed this

vegetable oils are very effective for sustainable machining applications under MQL conditions [23]. The integration of nanotechnology Machining performance is significantly increased with vegetable oil- based lubricants. The experimental investigations [25]. Nano Enhanced vegetable oils consisting of aluminum oxide nanoparticles Exhibition superior thermal conductivity and tribological behavior Compared to pure vegetable The oil [26]. The nanoparticles better heat dissipation from the cutting zone and worked as miniature rolling elements between the cutting tool and workpiece surface, this reduces friction and wear [57]. Experimental results demonstrate that nano- enhanced vegetable oil- based MQL systems created the lowest cutting temperature, at the very least surface roughness, and longest tool life between all lubrication conditions I investigated this study [65]. These findings Government this clearly nano- MQL systems represents a very promising direction for future sustainable machining technologies [35]. The experimental investigations Furthermore confirmed that based on vegetable oil MQL systems Significantly improved surface roughness and machining quality [18]. Effective lubrication is reduced. Frictional resistance and vibration During machining, as a result smoother surfaces and improved dimensional accuracy [43]. Improved chip morphology and improved chip evacuation was also observed under MQL conditions Because the lubrication is minimal. Chip- tool adhesion and thermal deformation [5]. Reduced cutting force Under vegetable oil MQL systems Contributed to further improved mechanical stability and lower energy consumption [23]. The researchers concluded that improved lubrication efficiency Increases machining productivity and machining quality directly below industrial machining operations [61]. Environmental analysis Held in this study demonstrated substantial sustainability advantages Associated with vegetable oil. MQL systems [54]. Conventional flood cooling systems utilize a large amount of mineral oil- based. Cutting fluids Who creates severe environmental pollution and hazardous waste generation [58]. Vegetable oil- based lubricants are biodegradable, renewable and non- toxic. Making them Environmentally compatible alternatives to conventional cutting fluids [49]. The reduced coolant consumption under MQL conditions Considerably less waste generation, Requirements for disposal of

coolant, and environmental contamination [31]. Scientists too observed that lower coolant mist generation better air quality and reduced occupational health hazards to machine operators [66]. These results indicate that vegetable oil- based MQL systems Strongly supports. Green manufacturing and sustainable industrial development [40]. The economic analysis performed under this study Further demonstrated industrial feasibility based on vegetable oils MQL systems [61]. Reduced lubricant consumption Significant reduction in the purchase of coolant, maintenance, storage, and disposal Expenditure [50]. Better tool life and reduced tool wear at the very least machine downtime and tool costs thus increase. Industrial productivity [16]. Better surface quality Even less the need to secondary finishing operations Value polishing and grinding, further down production cost and machining time [43]. Low cutting force and lower energy consumption Collaboration additional economic advantages by improving machining efficiency and to reduce power requirements [23]. The researchers concluded that vegetable oil- based MQL systems deliver long- term economic benefits at the same time as it improves environmental sustainability [54]. Despite numerous advantages, this study also identified certain challenges and limitations Associated with vegetable oil. MQL systems [53]. May contain vegetable oil. Oxidation instability and degradation at the extreme high machining temperatures [49]. Something vegetable oils also shows limited cooling capacity below severe machining conditions Difficult to cut materials and high-speed machining are involved. Operations [64]. Nano- enhanced lubricants are required. Proper dispersion techniques to maintain nanoparticle stability, which increases lubricant preparation complexity and the cost [35]. Further optimization of machining parameters, I. E lubricant flow rate, nozzle position, air pressure, and necessary to achieve cutting conditions maximum machining performance under MQL conditions [67].

These limitations Aspect it out continuous research and technological advancements Vegetable oil- based industrial applications are essential to improve performance. MQL systems [33]. Future scope based on vegetable oil MQL technology remains highly promising because industries worldwide Focuses quickly sustainable manufacturing and environmentally friendly machining technologies

[54]. Advances in nanotechnology, artificial intelligence, Smart lubrication systems, and hybrid cooling technologies Further improvements are expected. Lubrication efficiency and machining performance [36]. Researchers Currently developing chemically modified vegetable oils with improved oxidation stability and hybrid nano- lubricants capable to supply superior thermal conductivity and tribological behavior [20]. Intelligent MQL systems Integrated with sensors, automation and machine learning algorithms Expect to get better. Lubrication conditions According to automatic machining requirements [52]. The integration of Industry 4.0 technologies with sustainable lubrication systems will play a major role I future green manufacturing industries [40]. Overall, this research Obviously based on vegetable oil Minimum Quantity Lubrication Systems Provides an efficient, sustainable and economical feasible alternative to conventional flood Methods of cooling in machining operations [70]. Vegetable oil- based lubricants significantly improve machine performance by reducing friction. Tool wear, Lower the cutting temperature, minimize cutting force, to improve surface finish, and increase machining stability [16]. Nano Enhanced vegetable oils Improve further lubrication efficiency and thermal conductivity, Make it very suitable for them advanced machining applications [25]. Environmental benefits of biodegradable lubricants, together with the economic advantages of reduced coolant consumption and improved tool life, strongly supports the industrial apply of vegetable oil- based. MQL systems to future sustainable manufacturing applications [54]. So based on vegetable oil MQL technology represents a very promising approach to achieve environmentally responsible, energy efficient and high-performance machining operations. Modern manufacturing industries [33].

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