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Minimum Quantity Lubrication In Sustainable Machining: A Structured Literature Review, Industrial Relevance For Ludhiana, And Resource-Saving Implications For Small-Scale Industries

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Abstract: Minimum Quantity Lubrication (MQL) has emerged as a viable strategy for sustainable machining because it drastically reduces cutting-fluid consumption while maintaining acceptable machining performance. This paper presents a structured review of MQL focusing on lubrication mechanisms, machining responses, process-wise applicability, implementation barriers, and industrial relevance for small-scale manufacturing industries, with special emphasis on the Ludhiana district in Punjab, India. The review synthesizes evidence from peer-reviewed studies on how MQL influences cutting force, tool wear, surface quality, thermal behavior, and process stability across turning, milling, drilling, and grinding operations. It further examines the functional roles of mineral, vegetable, synthetic-ester, and nano-enhanced lubricants, and compares MQL with dry, flood, and cryogenic cooling modes in terms of cooling capacity, lubrication quality, cost, and environmental impact. Finally, the paper discusses adoption barriers for micro and small enterprises in Ludhiana, including awareness gaps, retrofit feasibility, and economic hesitation, and outlines a practical roadmap for gradual implementation. The review concludes that MQL is not merely a laboratory concept but a realistic intermediate pathway toward sustainable machining in resource-sensitive industrial clusters, provided that technical, organizational, and economic factors are addressed coherently.

***Index Terms* -** Minimum Quantity Lubrication, MQL, sustainable machining, green manufacturing, cutting fluids, tool wear, surface roughness, Ludhiana industries, small-scale manufacturing.

1. Introduction

1.1 Background and motivation

Machining operations rely on controlled lubrication and heat management to maintain dimensional accuracy, protect cutting tools, and achieve acceptable surface integrity. Conventional flood cooling has historically dominated industrial practice because large fluid volumes can simultaneously remove heat and provide boundary lubrication at the cutting zone. However, high coolant consumption increases purchase cost, storage requirements, maintenance burden, disposal complexity, and occupational exposure, issues that are particularly severe for small and medium enterprises (SMEs) with limited infrastructure for fluid management.

1.2 Problem statement

In many small-scale machining units, coolant use is guided more by experience than by optimized engineering practice, leading to overuse of cutting fluids and inefficient disposal practices. Rising costs of coolants, stricter environmental regulations, and pressure to improve workplace health and safety are forcing these industries to reconsider traditional lubrication strategies. There is therefore a strong need for lubrication concepts that significantly reduce fluid consumption without compromising machining performance, tool life, or product quality.

1.3 Concept of Minimum Quantity Lubrication

Minimum Quantity Lubrication addresses these challenges by supplying a very small quantity of lubricant directly to the cutting zone, typically in the form of a finely atomized air–oil mixture. Instead of immersing the entire tool–workpiece region in fluid, MQL relies on targeted delivery to the tool–chip and tool–workpiece interfaces so that friction is reduced at the source while total fluid volume is minimized. From a sustainability perspective, this approach attempts to maintain or improve machining efficiency while sharply lowering total lubricant consumption and the associated environmental burden.

1.4 Industrial context: Ludhiana manufacturing cluster

Ludhiana district in Punjab, India, is a prominent industrial cluster characterized by a dense concentration of micro, small, and medium machining-based enterprises producing bicycle components, automotive parts, machine tools, fasteners, and general metal products. Many of these units continue to use conventional flood cooling or semi-controlled oil application methods and operate under tight economic margins with limited waste-handling and mist-control infrastructure. In this context, MQL represents not only a technical alternative but also a potential pathway for resource conservation, cleaner shop-floor conditions, and incremental modernization without full replacement of existing machine tools.

1.5 Research gap

Numerous experimental and review papers have documented the tribological benefits of MQL, including reduced cutting force, improved tool life, better surface finish, and lower fluid consumption across various machining processes and lubricant formulations. However, much of the reported work is laboratory-centered and parameter-focused, with relatively limited attention to real adoption behavior, workshop-level constraints, operator skills, retrofit feasibility, and region-specific implementation in SME clusters such as Ludhiana. There is a need for a review that integrates technical evidence with an explicit industrial and regional perspective.

1.6 Objectives and contributions

This paper pursues the following objectives:

- To summarize the fundamentals and tribological mechanisms of MQL as a near-dry lubrication strategy.
- To synthesize reported performance effects of MQL on cutting force, tool wear, surface roughness, temperature, and process stability across major machining processes.
- To analyze the roles of different lubricant types, including mineral, vegetable, synthetic ester, and nano-enhanced fluids, in MQL systems.
- To compare MQL with dry, flood, and cryogenic cooling modes in terms of technical behavior, cost, and environmental impact.
- To discuss adoption barriers and practical challenges for small-scale machining industries, with a case focus on Ludhiana district.
- To propose a structured roadmap for introducing MQL in resource-sensitive industrial clusters.

2 Review methodology

2.1 Review design

This work is designed as a structured literature review of MQL in machining processes with emphasis on sustainable manufacturing and SME-oriented implementation. The review does not perform a formal statistical meta-analysis but aims to systematically capture and synthesize trends, recurring findings, and gaps reported in peer-reviewed literature.

2.2 Data sources

Relevant publications were identified through scientific databases such as Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar, using combinations of MQL-related keywords. Additional references were traced from the citation lists of key review articles and highly cited experimental studies on MQL and hybrid cooling–lubrication strategies.

2.3 Search strategy

Typical search queries included phrases such as “minimum quantity lubrication”, “near-dry machining”, “MQL turning”, “MQL milling”, “MQL drilling”, “MQL grinding”, “nanofluid MQL”, and “sustainable machining lubrication”. Searches were restricted to English-language publications and focused on the period from approximately 2002 to 2025, covering the evolution from early experimental studies to recent comprehensive reviews and nano-enhanced MQL investigations.

2.4 Inclusion and exclusion criteria

Studies were included if they: (i) investigated MQL or hybrid MQL-based cooling–lubrication in metal cutting or grinding; (ii) reported at least one machining performance indicator such as cutting force, tool wear, surface roughness, temperature, or chip behavior; or (iii) provided review-level discussion of lubrication strategies in sustainable machining. Papers were excluded if they focused exclusively on unrelated processes, lacked machining-related outcomes, or duplicated earlier work without new analysis.

2.5 Study selection and classification

From the initial search results, titles and abstracts were screened for relevance, and full texts were examined when necessary to confirm eligibility. The selected studies were then classified along five dimensions: machining process (turning, milling, drilling, grinding), lubricant type (mineral, vegetable, synthetic ester, nano-enhanced), workpiece material, primary response variables, and industrial orientation (laboratory vs. field or SME-focused).

Table 1. Classification of representative MQL studies by process, lubricant type, and main findings.

Ref. ID	Year	Machining process	Workpiece material	Lubricant type	Main response variables	Industrial orientation
R1	2002	Milling	Alloy steel	Mineral oil	Cutting force, tool wear, surface roughness	Laboratory
R2	2006	Turning	AISI 4340 steel	Vegetable oil	Tool wear, surface roughness, dimensional deviation	Laboratory
R3	2009	Turning	AISI 9310 alloy steel	Vegetable oil	Tool wear, cutting temperature, chip morphology	Laboratory
R4	2010	Grinding	Hardened steel	Mineral oil, hybrid MQL–CO_2	Grinding forces, surface integrity, thermal damage	Laboratory

Ref. ID	Year	Machining process	Workpiece material	Lubricant type	Main response variables	Industrial orientation
R5	2013	Turning	AISI 4140 steel	Mineral oil MQL	Cutting temperature, wear mechanisms, tool life	Laboratory
R6	2014	Turning	Difficult-to-cut alloy	Vegetable oil MQL	Multi-response optimization of MQL parameters	Laboratory
R7	2016	Milling	Various engineering alloys	Nanofluid MQL	Tribology, heat transfer, tool wear	Laboratory
R8	2017	Turning / milling	Various	Hybrid cooling–lubrication	Productivity, energy use, sustainability indicators	Review
R9	2020	Various processes	Various	Multiple (mineral, vegetable, nano)	Ecological, economic, technological assessment of MQL	Review
R10	2023–2025	Various	Various	Multiple	State-of-the-art of MQL and green machining	Review / perspective

3 Fundamentals and mechanisms of MQL

3.1 Definition and working principle
MQL is typically described as a near-dry machining approach in which a small quantity of lubricant, often a few milliliters per hour, is delivered to the cutting zone through a compressed air stream. The objective is to create a lubricating film at the critical contact interfaces while minimizing bulk fluid flooding and associated handling requirements.

3.2 Air–oil delivery and interface access
The performance of MQL depends strongly on the ability of atomized droplets to reach and remain at the tool–chip and tool–workpiece interfaces. Air-assisted transport must impart sufficient momentum to the droplets to penetrate into narrow contact zones without scattering them away, while interface wetting must be adequate to maintain a stable lubricating layer during cutting.

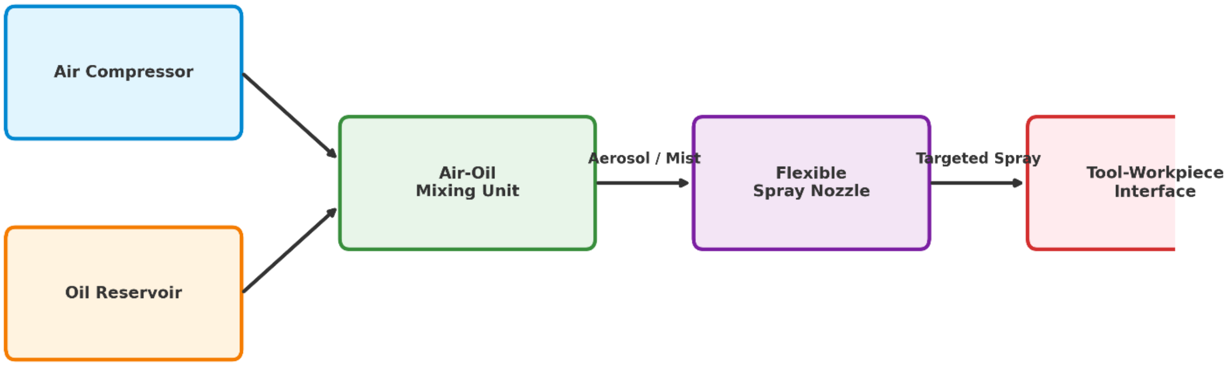
3.3 Tribological effects
When a thin lubricating film forms under MQL, the coefficient of friction at contact surfaces is reduced, sliding becomes smoother, and the tendency for adhesion and built-up edge formation decreases. This directly influences chip flow, contact stresses, and the mechanical loading on the cutting tool, which in turn affects tool wear patterns and surface finish.

3.4 Thermal behavior and heat generation
In machining, heat is generated primarily by plastic deformation of the work material, friction at the tool–chip interface, and rubbing of the flank face against the newly machined surface. Whereas flood cooling focuses on bulk heat removal, MQL primarily reduces heat generation by lowering frictional dissipation at the source, assisted by limited convective cooling from the air stream.

3.5 System parameters and setup sensitivity

Key controllable parameters in MQL systems include nozzle orientation, stand-off distance, air pressure, lubricant flow rate, droplet size distribution, and synchronization with chip-flow direction. Inadequate nozzle placement or poorly chosen operating parameters can lead to lubricant loss before reaching the tool tip, insufficient penetration, or excessive droplet scattering, which significantly degrades MQL performance.

Figure 1. Conceptual schematic of an MQL system



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4 Performance effects of MQL in machining

4.1 Cutting forces

Multiple studies report that MQL can reduce main cutting force components compared with dry machining due to improved lubrication at the tool–chip interface. Lower cutting force contributes to smoother operation, reduced spindle load, and can be particularly beneficial for small workshops where machine-tool rigidity and power margins are limited.

4.2 Tool wear and tool life

MQL often delays the onset of flank, crater, and adhesive wear under suitable conditions, thereby extending tool life and improving dimensional repeatability. Enhanced tool life translates into fewer tool changes, reduced downtime, and lower tooling cost per part, all of which are critical for resource-constrained SMEs.

4.3 Surface roughness and surface integrity

Improved lubrication reduces smearing and built-up edge, leading to smoother surfaces and better surface integrity compared with dry machining in many reported cases. The extent of improvement depends on cutting parameters, workpiece material, and lubricant formulation; careful tuning is required to ensure consistent roughness benefits.

4.4 Cutting temperature and chip morphology

Because frictional energy generation is reduced in MQL, temperatures at the tool–chip interface are often lower than in dry cutting, although flood cooling may still provide stronger bulk cooling in high-heat regimes. Changes in lubrication conditions are also associated with modified chip morphology and chip evacuation behavior, which can enhance or reduce process stability depending on the setup.

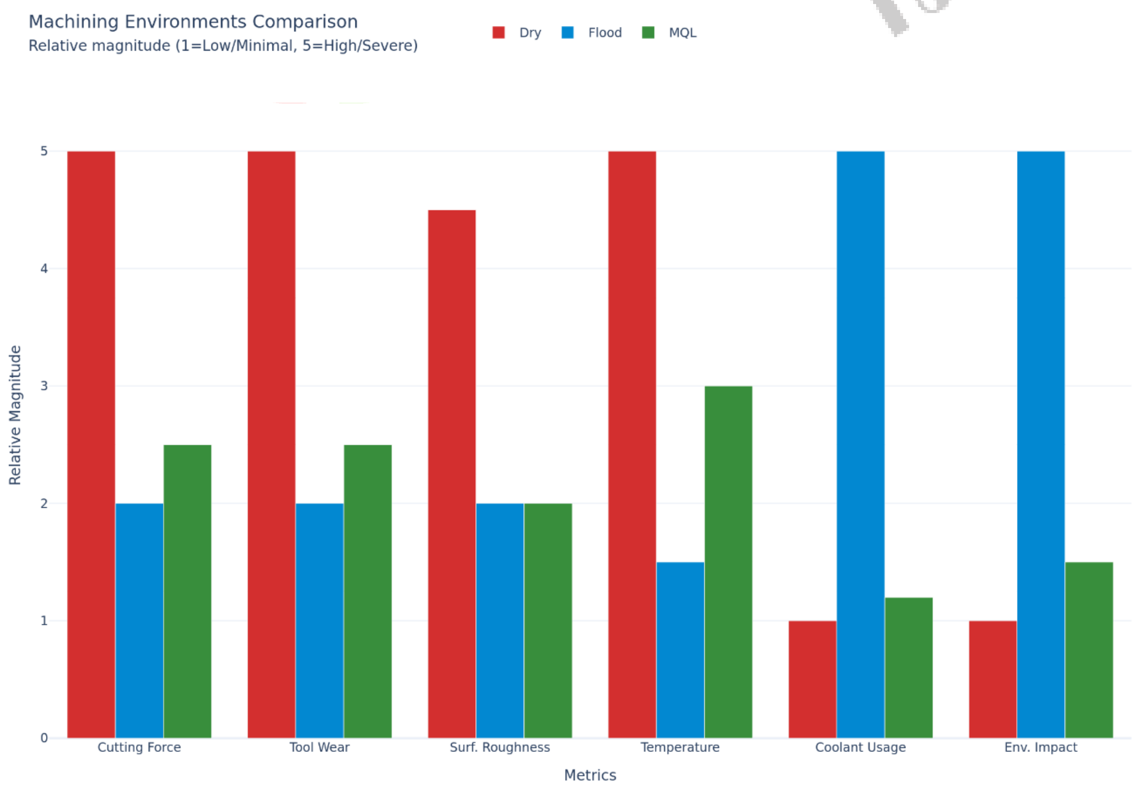
4.5 Process stability and vibration response

By reducing cutting forces and friction-induced chatter, MQL has the potential to improve dynamic stability in operations prone to vibration, such as slender turning or intermittent milling. Conversely, poorly directed sprays or unstable droplet delivery can lead to inconsistent lubrication and irregular cutting conditions.

Table 2. Typical performance trends of MQL relative to dry and flood machining

Response variable	MQL vs dry machining	MQL vs flood cooling	Remarks
Cutting force	Generally lower	Comparable or slightly higher	Depends on setup, material, and parameters
Tool wear / tool life	Reduced wear, longer life	Often comparable; sometimes slightly worse in extreme-heat jobs	Strongly affected by lubricant and nozzle design
Surface roughness	Improved surface finish	Often comparable	Sensitive to cutting conditions and BUE tendency
Cutting temperature	Lower than dry	Higher than flood in many cases	MQL reduces heat generation more than it removes heat
Chip behavior	More stable chip flow	Comparable	Geometry and chip breaker remain important
Process stability	Improved vs dry	Generally acceptable	Requires tuning of MQL parameters
Coolant use	Drastically lower	Much lower	Major advantage for SMEs and sustainability
Environmental impact	Lower than dry (less tool waste) and flood (less fluid)	Lower	Depends on lubricant type and mist control

Figure 2. Example radar chart of normalized performance indices



5 Lubricant types and functional roles in MQL

5.1 Mineral-oil-based lubricants

Mineral oils have historically been used due to their availability, established performance, and compatibility with existing machine-tool systems. However, environmental and health concerns associated with mineral-based fluids have motivated a shift toward more sustainable alternatives.

5.2 Vegetable-oil-based lubricants

Vegetable oils such as canola, soybean, and palm-based formulations offer high lubricity and are generally more biodegradable than mineral oils, making them attractive for green manufacturing. Several studies report that vegetable-oil-based MQL can outperform mineral oils in terms of surface finish and tool life for certain materials and cutting conditions.

5.3 Synthetic esters and engineered formulations

Synthetic esters are often tailored for stable viscosity, thermal behavior, and oxidation resistance, allowing consistent performance in engineered lubrication systems. Their predictable behavior is advantageous for industrial environments where reproducibility and process control are essential.

5.4 Nano-enhanced lubricants

Nano-additive-based lubricants introduce particles such as metal oxides, carbides, or solid lubricants into the base oil to enhance thermal conductivity, load-carrying capacity, and anti-wear properties. Research indicates that nano-enhanced MQL can maintain lubrication effectiveness under more severe cutting conditions, but concerns remain regarding cost, dispersion stability, and occupational exposure.

5.5 Practical selection criteria for SMEs

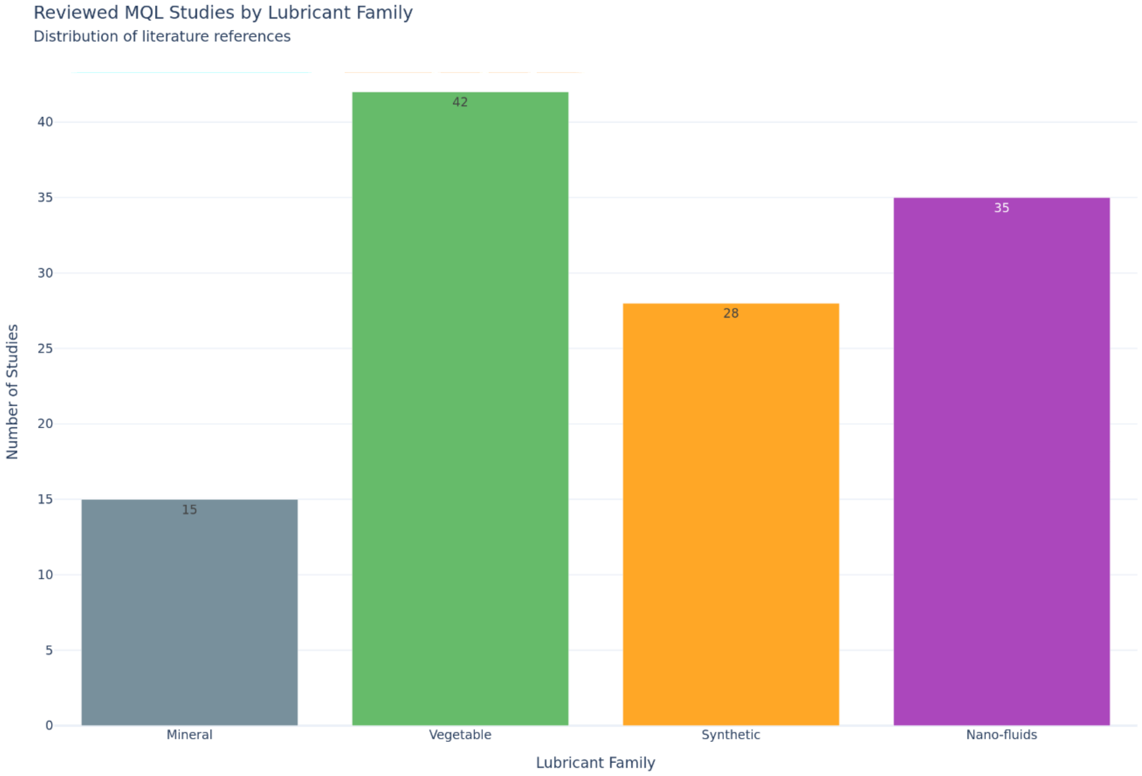
For small industries, lubricant selection cannot be based solely on laboratory performance; availability, storage stability, cost, operator familiarity, and compatibility with existing delivery systems are equally important. A lubricant that delivers excellent results in controlled experiments may still face adoption barriers if it is expensive, difficult to procure, or complex to manage in typical workshop environments.

Table 3. Practical comparison of lubricant types for MQL in SME environments

Lubricant type	Tribological performance	Biodegradability	Relative cost	Availability for SMEs	Handling and storage complexity	Typical suitability
Mineral oil	Good, well established	Low	Low–moderate	High	Low complexity, familiar	General-purpose MQL where sustainability demands are modest
Vegetable oil	Very good lubricity	High	Moderate	Increasing	Needs attention to oxidation and storage	Green manufacturing, small shops seeking eco-friendly image
Synthetic ester	Very good, stable	Medium	Higher	Moderate	Requires controlled storage	High-consistency industrial setups

Lubricant type	Tribological performance	Biodegradability	Relative cost	Availability for SMEs	Handling and storage complexity	Typical suitability
						requiring repeatability
Nano-enhanced fluids	Potentially excellent (wear, temperature)	Depends on base oil and particle	Higher	Limited / emerging	Higher complexity (dispersion, safety, filtration)	Advanced or high-severity operations; R&D or pilot use

Figure 3. Bar chart of number of reviewed studies by lubricant family



6 Applications across machining processes

6.1 Turning

Turning has been extensively used as a testbed for studying MQL because it offers a relatively simple geometry for measuring cutting force, temperature, tool wear, and surface quality. In many cases, MQL has demonstrated the ability to reduce oil consumption dramatically while maintaining or improving machining performance compared with dry conditions, especially for steels and common alloys.

6.2 Milling

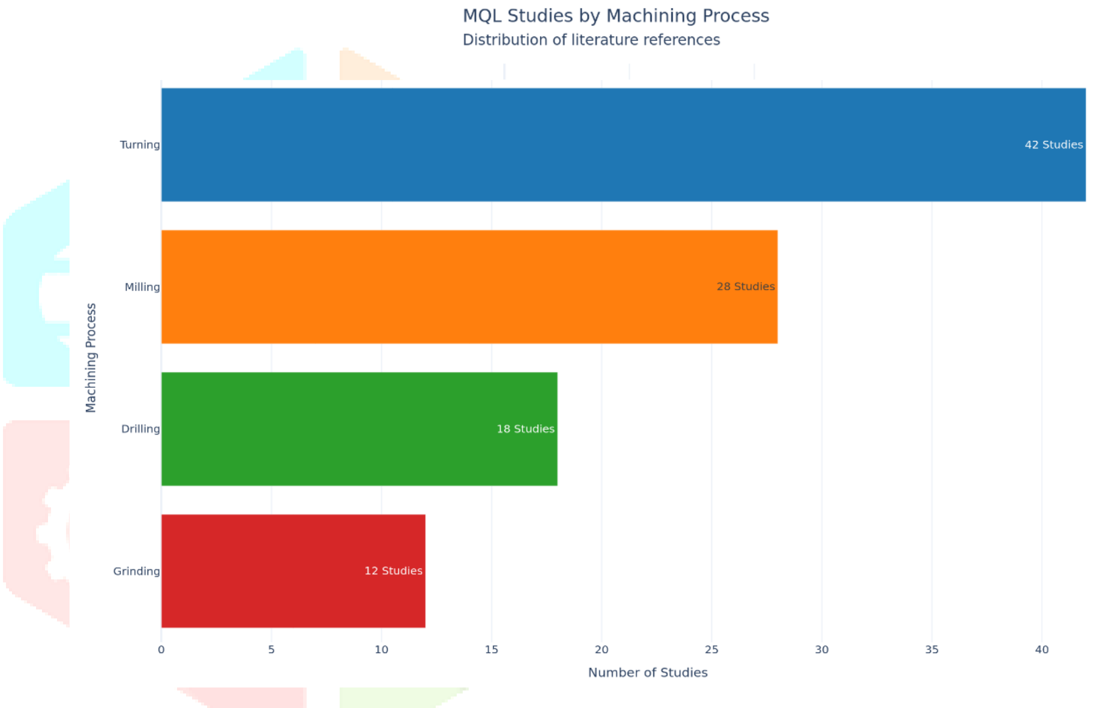
In milling, intermittent cutting and more complex chip evacuation make MQL implementation more challenging, particularly with respect to heat fluctuation and droplet access. Nevertheless, well-configured MQL systems have achieved improved edge conditions, acceptable surface finish, and reasonable thermal control in a range of milling applications.

6.3 Drilling
The main difficulty in drilling is delivering lubricant effectively into a confined and continuously deepening hole, which may require internal channels, custom nozzles, or higher air pressure. For suitable tool and nozzle designs, MQL has been reported to enhance hole quality and tool life compared with dry drilling, while using far less fluid than flood cooling.

6.4 Grinding
Grinding traditionally consumes large volumes of coolant due to high specific energy and heat generation; therefore, it has attracted significant interest for MQL-based fluid reduction. Studies on MQL grinding highlight the importance of precise nozzle placement and fluid formulation to avoid thermal damage while still reducing coolant consumption and environmental load.

6.5 Process-specific implementation guidelines
Different machining processes impose different requirements on droplet access, heat removal, chip flow, and contact conditions; thus, MQL implementation must be tailored rather than assumed to transfer directly from one process to another.

Figure 4. Process-wise distribution of reviewed MQL studies



7 Comparative analysis with other cooling and lubrication modes

7.1 Dry machining
Dry machining eliminates fluid use entirely, which removes coolant-related costs and disposal issues but can lead to higher friction, accelerated tool wear, increased cutting temperatures, and poorer surface finish under many cutting conditions. MQL offers a compromise by retaining the resource-saving benefits of low fluid use while still providing enough lubrication to mitigate these disadvantages.

7.2 Conventional flood cooling
Flood cooling provides high cooling capacity and robust lubrication but at the expense of large fluid consumption, complex handling, mist generation, and significant environmental burden. For many operations, MQL has been shown to achieve acceptable performance with a fraction of the fluid volume, although flood systems may still be preferred for extremely high-heat or high-speed conditions.

7.3 Cryogenic cooling
Cryogenic cooling, often using liquid nitrogen or carbon dioxide, provides very high cooling ability and can be effective for difficult-to-machine materials and high-temperature applications. However, cryogenic systems typically require specialized equipment, higher capital investment, and careful safety management, making them less accessible for small industries than retrofittable MQL setups.

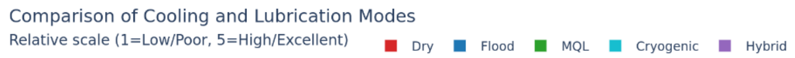
7.4 Hybrid and advanced techniques

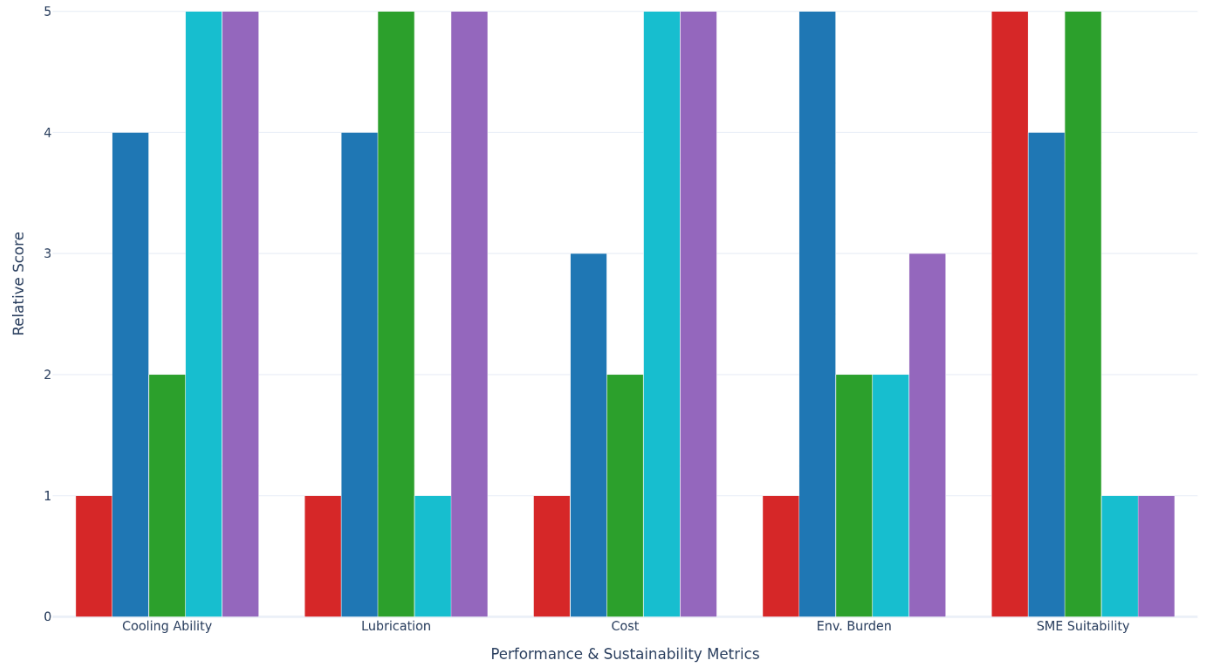
Hybrid strategies, such as MQL combined with cryogenic delivery or nanofluids, aim to leverage complementary advantages of different approaches to improve sustainable machining further. While promising, these methods are still evolving and may demand higher complexity, cost, and technical expertise than simple MQL systems.

Table 4. Comparative overview of cooling and lubrication strategies

Technique	Cooling ability	Lubrication quality	Relative cost	Environmental impact	SME suitability	Key remarks
Dry machining	Low	Very low	Low	High due to heat generation and tool waste	Limited	Eliminates coolant but can accelerate wear and degrade finish.
Flood cooling	High	High	High	High due to large fluid use, mist, and disposal	Moderate (if infrastructure exists)	Robust but fluid-intensive; requires tanks, pumps, and treatment.
MQL	Moderate	High	Moderate	Low because lubricant use is minimal	High	Good compromise between performance and resource use; retrofit-friendly.
Cryogenic cooling	Very high	Low–moderate	Very high	Low coolant residue, but high energy/system impacts	Low–moderate	Effective for difficult materials; needs specialized equipment.
Hybrid (e.g., MQL + CO_2, MQL + nanofluid)	High	High	Very high	Case-dependent	Experimental / advanced	Promising but complex; still under development.

Figure 5. Comparative radar chart of cooling/lubrication modes





8 Industrial relevance for Ludhiana district

8.1 Profile of machining-intensive SMEs

Ludhiana hosts a very large number of micro, small, and medium enterprises engaged in machining-intensive production of cycle parts, fasteners, automotive components, machine tools, and general metalworking. In such a dense cluster, even modest savings per machine or per shift can accumulate into significant regional resource conservation.

8.2 Resource conservation and process cleanliness

For these industries, excessive use of cutting fluids translates into higher direct costs, greater storage requirements, more complex disposal, and dirtier shop-floor conditions. MQL can contribute to reduced lubricant purchase, lower waste-handling burden, and cleaner working environments without forcing an immediate shift to expensive or disruptive alternatives.

8.3 Retrofit feasibility and infrastructure constraints

Many Ludhiana workshops operate older machine tools that were not designed for advanced coolant systems, yet they usually have access to compressed air and can potentially accommodate retrofittable spray nozzles. This makes MQL a more realistic transition technology than full cryogenic systems or sophisticated closed-loop flood-management platforms for such units.

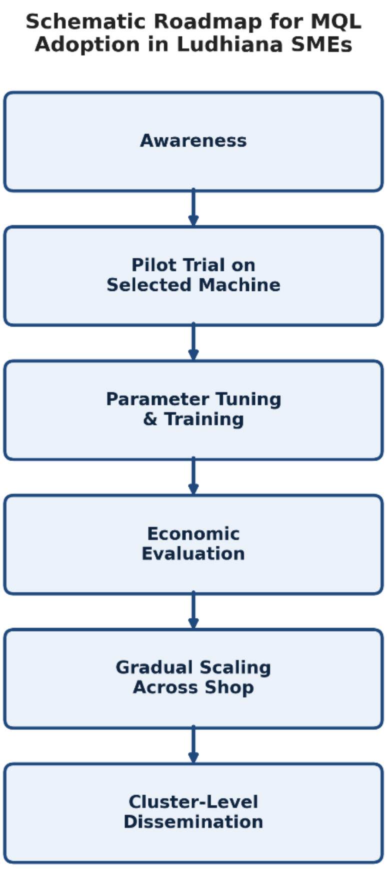
8.4 Perception and awareness

Awareness about MQL among workshop owners and operators may be limited, and there may be a perception that reduced fluid volume automatically implies higher risk or poorer machining quality. Focused awareness campaigns and demonstration projects are therefore crucial to change perceptions and build confidence in MQL-based operations.

Table 5. Typical characteristics of Ludhiana SMEs and implications for MQL

SME characteristic	Lubrication implication	MQL opportunity	Potential concern
Older machine tools with basic coolant systems	Limited provision for advanced coolant management	Retrofit external MQL spray nozzles using existing compressed air	Space for mounting, variation in machine condition
Tight operating margins and cost sensitivity	Coolant and disposal costs significantly affect profitability	Reduced fluid consumption and longer tool life can improve economics	Initial investment in MQL units and learning period
Limited waste treatment and disposal infrastructure	Risk of improper coolant disposal and shop contamination	Lower fluid volumes, cleaner floors, easier waste handling	Need for basic mist/exhaust arrangements
Strong reliance on operator experience	Process decisions based on habits rather than data	Simple, visible MQL systems can be tuned by operators after training	Initial resistance to perceived “low fluid” operation
Clustered industrial environment	Shared practices and peer influence	Demonstration at a few units can trigger cluster-wide adoption	If early pilots fail, negative perceptions may spread quickly

Figure 6. Schematic roadmap for MQL adoption in Ludhiana SMEs



9 Adoption barriers and implementation challenges

9.1 Technical and retrofit challenges

Technical barriers include nozzle placement difficulties, inconsistent droplet delivery, machine-tool condition variability, and uncertainty about suitable lubricants and settings for specific jobs. These challenges are amplified when machines are old or lack standardized mounting provisions for accessories.

9.2 Operator training and skill gaps

Successful MQL use depends on operators who can adjust air pressure, flow rate, nozzle orientation, and spray timing appropriately; without such training, systems may be installed but used suboptimally. Poorly tuned setups can produce disappointing results, leading to premature rejection of MQL as ineffective.

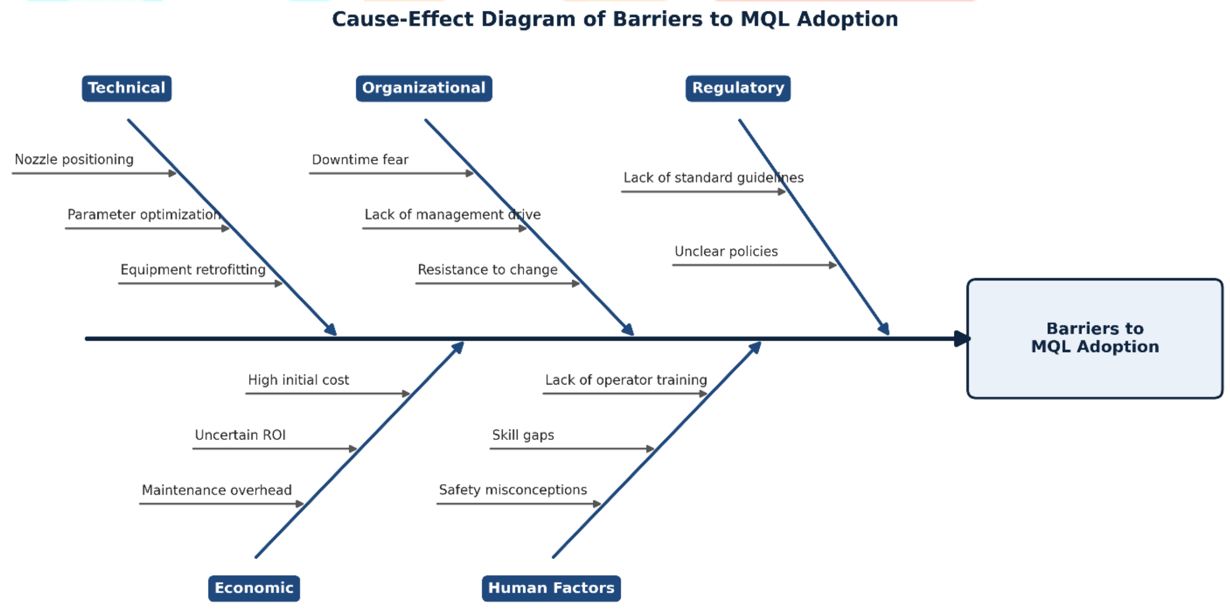
9.3 Economic hesitation and perceived risk

Even if MQL systems are not prohibitively expensive, owners may hesitate to invest without clear, quantified evidence of savings and performance reliability. SMEs usually prioritize short payback periods and may be reluctant to modify familiar processes unless benefits are convincingly demonstrated.

9.4 Health, safety, and regulatory aspects

While MQL reduces total fluid use and associated disposal, fine mist generation and airborne droplets must be controlled to protect worker health. Appropriate enclosure, extraction, and personal protective practices are therefore part of responsible MQL implementation.

Figure 7. Cause–effect diagram of barriers to MQL adoption



10 Systematic review perspective and evidence synthesis

10.1 Recurring technical themes

Across the reviewed literature, recurring themes include reduced lubricant consumption, improved tribological conditions, beneficial effects on tool wear and surface quality, and the critical importance of setup variables such as nozzle geometry and lubricant selection.

10.2 Gaps in real-world implementation data

In contrast, far fewer studies address real adoption behavior in SMEs, workshop-level constraints, operators' perceptions, or region-specific feasibility aspects. This creates a research gap between laboratory demonstration of MQL's potential and large-scale industrial deployment in clusters such as Ludhiana.

10.3 Transition argument for resource-sensitive regions

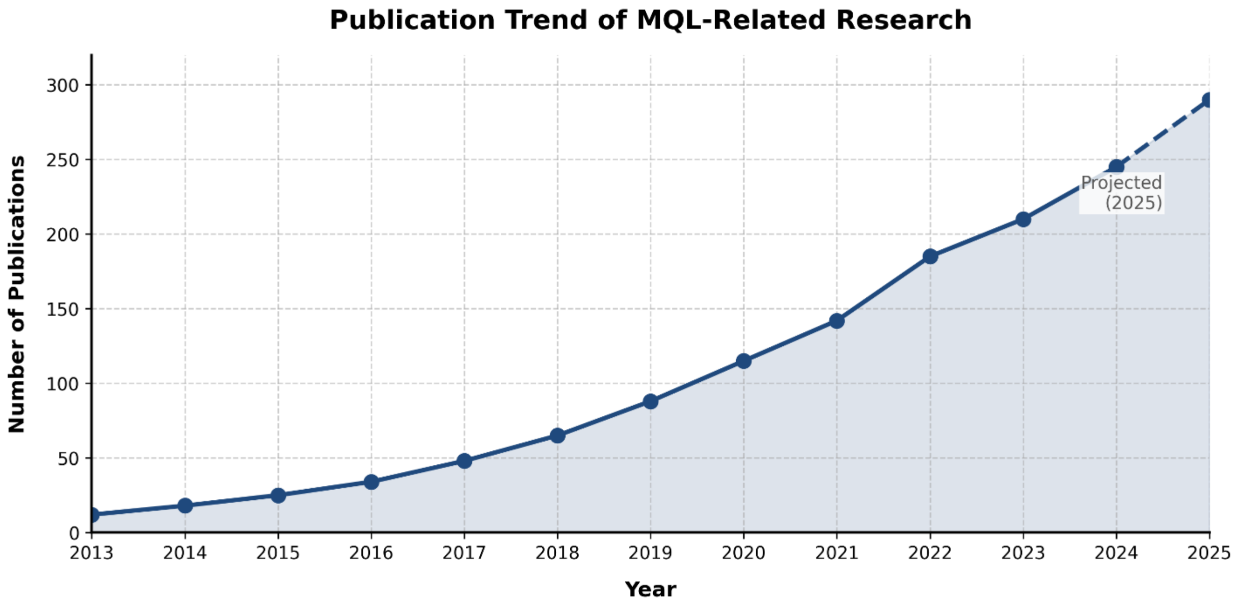
The evidence base is sufficiently strong to justify pilot implementations of MQL in resource-constrained industrial environments, but success will depend on tailored retrofit solutions, training, and economic support mechanisms. Hence, the review supports a practical transition argument rather than merely repeating technical feasibility demonstrations.

11 Results-oriented visual summaries

11.1 Publication trend in MQL research

A publication trend graph for MQL-related research showing increasing numbers of papers per year can illustrate the growing academic and industrial interest in this topic. This visual emphasizes that MQL is an evolving field with expanding literature and technical diversity.

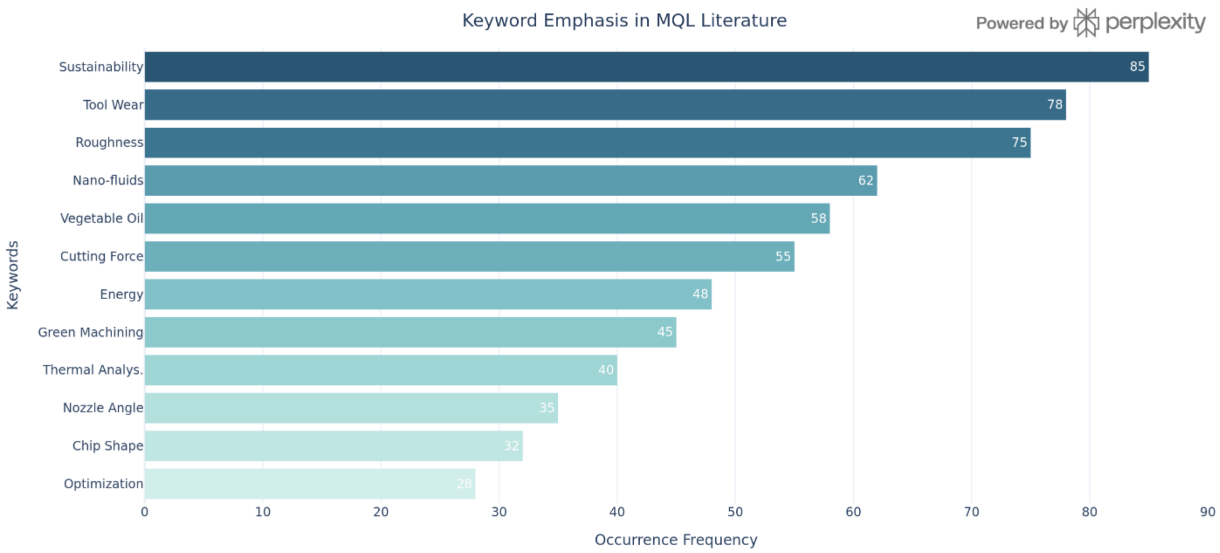
Figure 8. Publication trend of MQL-related research



11.2 Keyword emphasis and thematic clusters

A keyword-emphasis plot can indicate dominant themes such as sustainability, nanofluids, tool wear, surface roughness, and hybrid lubrication methodologies. This helps readers quickly perceive the main research directions and identify emerging subtopics.

Figure 9. Keyword emphasis in MQL literature



11.3 Distribution across machining processes

A process-wise distribution figure can show that turning and milling account for the majority of MQL studies, with drilling and grinding representing smaller but significant segments. This distribution suggests areas where further research on less-studied processes or materials would be valuable.

11.4 Summary table for quick comparison

A comparative table of cooling and lubrication approaches (dry, flood, MQL, cryogenic, hybrid) can concisely present differences in cooling ability, lubrication quality, relative cost, environmental impact, and SME suitability. This table links technical characteristics with practical decision-making in workshop environments.

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12 Limitations and future research directions

12.1 Limitations of the present review

The present review synthesizes a broad body of MQL literature but does not perform a quantitative meta-analysis of effect sizes, nor does it include new experimental data or field measurements from Ludhiana workshops. It is also limited by the availability and accessibility of published studies, which may introduce publication bias toward successful or positive results.

12.2 Need for field and pilot studies

Future work should include structured field studies and pilot implementations of MQL in representative Ludhiana SMEs to quantify real-world savings in fluid consumption, tool life, energy use, and environmental burden. Such work should record operator feedback, retrofit challenges, and payback periods to support evidence-based adoption decisions.

12.3 Modelling and optimization opportunities

There is scope for integrated modelling frameworks that combine tribological models, thermal analysis, and economic evaluation to optimize MQL parameters for typical machines and products in Ludhiana. Optimization studies using multi-objective techniques can help balance productivity, cost, and sustainability criteria.

12.4 Health and exposure assessments

Research on the health implications of prolonged exposure to MQL mist and airborne nanoparticles, particularly in confined SME workshops, remains limited and deserves more systematic investigation. Establishing guidelines for safe operating conditions, enclosure design, and exhaust systems will further support responsible MQL adoption.

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13 Conclusion

Minimum Quantity Lubrication represents a technically credible and practically relevant pathway toward sustainable machining, especially for small and medium enterprises operating under resource constraints. By focusing on targeted lubrication and tribological efficiency rather than high-volume fluid flooding, MQL can drastically reduce lubricant consumption while still supporting essential machining requirements such as friction control, tool protection, and surface quality.

For industrial clusters such as Ludhiana, where a large number of machining-oriented SMEs operate with limited facilities for coolant management, MQL offers a gradual and retrofit-friendly route toward cleaner and more sustainable production practices. Realizing this potential, however, depends on overcoming barriers related to awareness, operator training, retrofit feasibility, and economic hesitation through well-designed demonstrations, capacity building, and policy support.

Overall, the literature and industrial context together indicate that MQL should be viewed not simply as an academic topic but as a practical intermediate technology for aligning machining operations with broader goals of resource conservation and green manufacturing in emerging industrial regions.

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