

Sustainable Machining in the Era of Industry 5.0: A Unified Review of Minimum Quantity Lubrication, Nanofluids, and Human-Centric Process Optimisation for Net-Zero Manufacturing

Ignatius Ekengwu * and Dara Ezechi Jude

Department of Mechanical Engineering, Nnamdi Azikiwe University, Awka 420110, Nigeria

* Correspondence: ie.ekengwu@unizik.edu.ng

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Abstract: Conventional flood cooling remains the dominant lubrication strategy in machining workshops worldwide, despite more than three decades of documented evidence concerning its environmental and occupational health costs. A single production facility may consume thousands of litres of cutting fluid annually, and the aerosol generated at the work zone carries well-documented associations with respiratory disease, dermatitis, and carcinogen exposure for operators. Over the same period, three categories of technical alternative have each developed substantial evidence bases: minimum quantity lubrication (MQL), nanofluid cutting fluids, and AI-driven process optimisation. No prior review has examined how these three strands fit together, or situated their integration within the Industry 5.0 framework, which holds that manufacturing must serve human well-being and ecological sustainability alongside productivity. This paper addresses that gap. Drawing on 125 primary publications from 2010 to 2025 identified through systematic database searches (methodology described in Section 1.1), the reviewed evidence indicates that nanofluid MQL can reduce cutting fluid consumption by 97 to 99.7 per cent relative to conventional flood cooling while achieving comparable or improved surface finish, tool wear, and cutting force outcomes across titanium alloys, nickel superalloys, stainless steels, and aluminium. This review assesses six nanoparticle classes in bio-based carrier fluids—including locally available West African oils that have received limited attention in the international literature—and examines AI and machine learning approaches for MQL optimisation with explicit attention to worker health outcomes. Eight research gaps are identified and a proposed three-horizon research agenda towards measurably low-impact machining practice by 2035 is presented.

Keywords: minimum quantity lubrication; nanofluids; sustainable machining; Industry 5.0; bio-based lubricants; artificial intelligence; net-zero manufacturing

1. Introduction

Flood cooling—the delivery of large volumes of cutting fluid directly to the machining zone—remains the dominant lubrication strategy in manufacturing workshops worldwide, despite substantial documented evidence of its environmental and occupational health costs. Comparative surveys have identified that a significant proportion of conventional flood cooling environments generate airborne metalworking fluid aerosol concentrations exceeding the limits recommended by national occupational health authorities [1]. Life cycle



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assessments consistently show that fluid production, use, treatment, and disposal represent a major component of the total environmental burden of machined components [2]. These findings have been available in the literature for more than three decades. The persistence of flood cooling as the default approach, in the face of this evidence, reflects a combination of capital inertia, the absence of standardised alternatives, and—until recently—the absence of validated alternatives that could match flood cooling on machining performance. The technical record has changed significantly over the past two decades, as the sections that follow document.

The Industry 5.0 framework [3] establishes the mandate for this synthesis, treating human well-being and ecological sustainability as primary manufacturing objectives alongside productivity. What makes the current moment different from earlier periods of MQL advocacy is the convergence of three independently mature technical threads. Minimum quantity lubrication has been validated across dozens of material-process combinations over the past two decades, delivering cutting fluid as a controlled aerosol at 50 to 500 mL/h rather than the tens of litres per hour typical of flood systems [4–7]. Nanofluid cutting fluids—which suspend thermally and tribologically active nanoparticles in bio-based carrier oils—extend MQL performance further [8–10]. Machine learning tools can now predict surface finish, tool wear, cutting temperature, and energy consumption with accuracy comparable to physical experimentation, and optimise all of those outputs simultaneously [11–13]—including worker health outcomes that conventional process optimisation has largely treated as outside its scope, integrating all three threads within a design philosophy that treats human well-being and sustainability as primary objectives rather than constraints [14].

To situate this review's contribution, a brief mapping of what prior reviews covered and what they left out is helpful. Eltaggaz et al. [5] compared dry, flood, and MQL cooling strategies for tool life and surface roughness in machining of difficult-to-cut alloys but did not address nanofluid formulation or AI optimisation. Shokrani et al. [15] examined environmentally conscious machining broadly, including cryogenic and near-dry approaches, but without an Industry 5.0 framing or worker health as an optimisation objective. Liu et al. [11] and Manikanta et al. [12] reviewed machine learning in machining, but neither integrated these with MQL fluid design or worker health considerations. No prior review appears to have assembled a unified treatment of how MQL, nanofluids, and AI optimisation fit together within an Industry 5.0 framework treating human-centricity, sustainability, and resilience as co-equal pillars alongside technical performance. This synthesis attempts to address that gap. The novelty rests on integration and framing, not on original experimental data; all performance evidence is drawn from the cited primary literature. The evidence base for different components of this framework is uneven, and this is stated explicitly where it is thin. To manage repetition, four recurring themes are flagged here and developed progressively: (1) the worker health dimension—Sections 2, 5.3, and 6; (2) the Industry 5.0 framework—Section 5; (3) limitations of flood cooling—Sections 2 and 4; and (4) the evidence base and limits of bio-based nanofluid MQL—Sections 3, 6, and 7 [16].

Scope and objectives. Three key terms are used throughout this review and are defined here for precision. Standard MQL refers to the delivery of a conventional (non-nano) cutting fluid—typically a vegetable or mineral oil—as a controlled aerosol at flow rates of 50 to 500 mL/h, replacing flood cooling without altering fluid chemistry. Nanofluid MQL refers to MQL using a cutting fluid in which solid nanoparticles (1–100 nm) are stably dispersed in a bio-based or synthetic base fluid, enhancing its thermal and tribological performance. AI-optimised Industry 5.0 MQL refers to a nanofluid MQL system whose parameters (flow rate, air pressure, nozzle angle, nanoparticle type and concentration) are continuously or periodically adjusted by a machine learning model, with explicit inclusion of worker health metrics alongside technical performance metrics as optimisation objectives. This review covers turning, milling, grinding, and drilling of titanium alloys, nickel superalloys, stainless steels, aluminium alloys, and engineering polymers. It draws on 125 verified primary publications from 2010 to 2025, identified through systematic searches of Scopus and Web of Science (methodology in Section 1.1). The specific contributions are: (1) what is believed to be the first unified synthesis of MQL, nanofluid, and AI optimisation within an Industry 5.0 framework; (2) a comparative performance synthesis across lubricant types, workpiece materials, and machining operations; (3) a comparative evaluation of bio-based lubricants with particular attention to locally available West African sources; (4) a review of human-centric health and ergonomic outcomes that conventional machining optimisation has largely overlooked; and (5) a proposed three-horizon research agenda grounded in the reviewed evidence. The evolution of machining paradigms underpinning this framework is illustrated in Figure 1 [17,18].

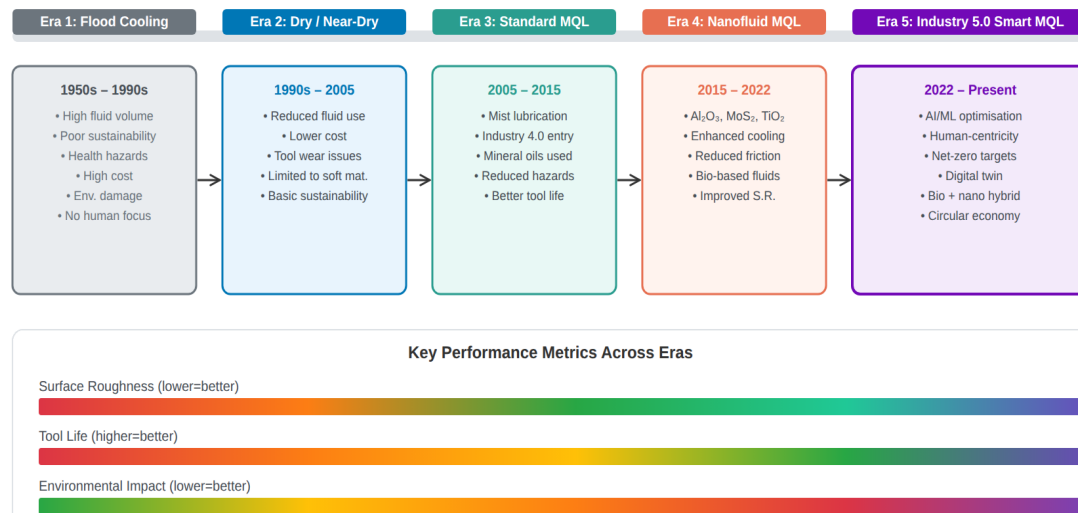


Figure 1. Evolution of machining paradigms from conventional flood cooling through dry and near-dry machining, standard MQL, nanofluid-enhanced MQL, to the emerging Industry 5.0 intelligent and human-centric MQL framework. Each era is characterised by its defining technical features and key performance and sustainability limitations. The transition from Era 4 to Era 5 represents a qualitative shift from technical performance optimisation to a holistic framework that simultaneously addresses machining quality, worker health, environmental impact, and digital intelligence. Figure created based on data reported in [19].

Literature Search and Review Methodology

This review was conducted as a structured narrative review of the peer-reviewed literature on minimum quantity lubrication, nanofluid cutting fluids, artificial intelligence optimisation in machining, and Industry 5.0 frameworks as applied to manufacturing sustainability and worker health. The review is not a formal systematic review or meta-analysis; it is a narrative synthesis that draws on a defined, documented literature corpus to develop an integrated theoretical and practical framework.

Search databases: Scopus and Web of Science (Core Collection). **Search period:** 2010 to 2025. **Search strings** applied included combinations of the following terms: (“minimum quantity lubrication” OR “MQL”) AND (“nanofluid” OR “nanoparticle” OR “bio-based lubricant”); (“sustainable machining” OR “green machining”) AND (“Industry 5.0” OR “human-centric”); (“MQL” OR “nanofluid machining”) AND (“machine learning” OR “artificial intelligence” OR “digital twin”); (“cutting fluid” OR “metalworking fluid”) AND (“worker health” OR “aerosol exposure” OR “occupational health”). Boolean logic (AND/OR) was applied throughout; truncation and wildcard operators were used where supported by each database. **Search date:** December 2024 [20].

Screening and inclusion criteria: Records were screened at title and abstract level. **Inclusion criteria** were: (1) primary research articles or authoritative review papers; (2) published in English in peer-reviewed journals; (3) directly addressing MQL system design, nanofluid composition or performance, bio-based lubricants, AI/ML optimisation for machining, Industry 5.0 frameworks, or occupational health in machining environments; (4) providing quantitative experimental data or rigorous conceptual frameworks. **Exclusion criteria** were: (1) conference abstracts without full-paper data; (2) purely theoretical studies without experimental or field validation; (3) studies not directly relevant to the machining or lubrication context. Duplicate records identified across both databases were removed before screening. The screening sequence was as follows: initial database searches retrieved approximately 1840 records in total (approximately 1040 from Scopus and 800 from Web of Science); after automated deduplication, 1312 unique records remained; title and abstract screening excluded 1097 records as not meeting inclusion criteria; 215 full-text articles were assessed for eligibility; of these, 90 were excluded on the basis of the exclusion criteria listed above (primarily conference abstracts without full-paper data, purely theoretical studies, or studies not directly relevant to the machining or lubrication context); a final corpus of 125 primary publications passed all screening criteria and form the verified literature base of this review. Foundational references (pre-2010) were included selectively where they established core concepts cited throughout the field (for example, the Choi and Eastman nanofluid foundational paper).

Data synthesis approach: Quantitative performance ranges reported throughout this review (for example, percentage reductions in Ra, VB, or aerosol concentration) represent the observed range across multiple independent studies that met inclusion criteria, not weighted means or formal meta-analytic estimates. Where a single study is cited to illustrate a specific finding, this is indicated by naming the study; where a range is reported,

it reflects the spread across all studies in the corpus addressing that variable. Figures in this paper are conceptual syntheses and illustrative normalised comparisons derived from the reviewed literature data; they are not the product of a statistical meta-analysis and should be read as representative trend summaries. Critical appraisal of individual studies is discussed qualitatively where study design strength or limitations are relevant to interpreting the evidence.

Table 1 below provides a summary appraisal of evidence strength across the six principal thematic areas of this review. This classification reflects the quantity, consistency, and methodological quality of the studies contributing to each theme, and is intended to help readers calibrate confidence in the reported findings accordingly (Table 1).

Table 1. Summary appraisal of evidence strength across the six principal thematic areas of this review.

Thematic Area	Evidence Strength	Basis for Classification
Technical Performance (surface finish, tool wear, cutting force)	Strong	Multiple independent studies across major engineering alloys (Ti-6Al-4V, Inconel 718/625, AISI stainless steels, AA6082); consistent directional findings; well-characterised experimental conditions.
Life Cycle Assessment (LCA)	Moderate	Consistent CO ₂ and waste reduction findings across reviewed LCA studies; absolute values sensitive to system boundary assumptions; limited independent replication of full lifecycle models.
Aerosol Exposure and Worker Health	Moderate	Short-term aerosol and noise measurements consistently favour MQL; longitudinal epidemiological data from real production environments absent from the reviewed literature.
AI/ML Process Control	Moderate	Strong predictive accuracy demonstrated in offline and simulation studies; real-time closed-loop validation at industrial scale demonstrated in only a small number of studies; closed-loop industrial deployments not yet reported.
Digital Twins	Limited	No coupled digital twin model validated against physical MQL machining measurements in the reviewed literature; concept supported by component physics models only [21].
West African Bio-Lubricants	Limited	Promising proof-of-concept studies for neem, palm kernel, and tiger nut oils; independent replication, broader material coverage, and standardised characterisation still needed before firm industrial recommendations.

2. Minimum Quantity Lubrication: Principles, Mechanisms, and System Design

2.1. Physical Principles of MQL

What distinguishes MQL from flood cooling is not just volume but precision of delivery. Where flood cooling submerges the entire work zone in fluid, MQL directs a precisely metered aerosol—compressed air at 4 to 8 bar carrying 50 to 500 mL of cutting fluid per hour—straight to the tool-chip and tool-workpiece interfaces where friction and heat actually originate [22]. The aerosol droplets, typically 5 to 50 micrometres in diameter, reach the contact zone through a nozzle positioned at an angle of 15 to 75 degrees from the machined surface; this geometry, together with air pressure and flow rate, governs how effectively lubrication and cooling reach the primary heat source [23]. The result is targeted delivery rather than saturation, and this targeting is the source of MQL's environmental and health advantages, not merely its reduced volume.

The heat transfer physics of MQL differ fundamentally from flood cooling. In flood cooling, heat removal is primarily convective: large volumes of flowing fluid carry heat away from the cutting zone. In MQL, two mechanisms operate together. First, evaporative cooling: fine aerosol droplets absorb latent heat as they contact the hot cutting zone. Second, boundary lubrication: the fluid forms an adsorption film on tool and workpiece surfaces, reducing the frictional heat generated at source [24]. The outcome is that MQL can achieve lower cutting temperatures not in spite of using less fluid, but partly because the fluid it does use reaches the primary heat source more precisely. Reductions in cutting temperature of 30 to 45 per cent relative to flood cooling have been reported across a range of work materials and cutting conditions in the reviewed literature [6,25].

Beyond evaporative cooling and boundary lubrication, certain cutting fluid components—particularly the fatty acid constituents of vegetable-based oils—react with the freshly exposed metal surface during cutting to form thin, low-friction films that suppress adhesive wear and built-up edge formation. This tribochemical mechanism is the primary driver of surface quality improvement when machining ductile materials such as titanium and nickel alloys [26].

2.2. MQL System Components and Parameters

A complete MQL system has four functional elements: the air supply and pressure regulation stage, the fluid metering and reservoir stage, the mixing and atomisation chamber, and the delivery nozzle [27]. In conventional MQL systems these elements are static—fixed nozzle position, fixed flow rate, fixed pressure for a given setup. In an Industry 5.0 intelligent MQL system, all four elements are dynamically controlled by the AI layer described in Section 5, with real-time feedback from force, temperature, vibration, and acoustic emission sensors at the cutting zone driving continuous parameter adjustment [28].

Air pressure governs atomisation quality and the momentum of the aerosol jet. Too low a pressure produces large droplets that fail to penetrate the tool-chip contact zone; too high a pressure generates fine mist that escapes the cutting zone and elevates workplace aerosol concentrations. For most machining operations the optimum lies between 4 and 6 bar, with pressures of 6 to 8 bar occasionally beneficial at high cutting speeds [22].

Flow rate is among the most consequential MQL parameters for sustainability outcomes. Below 50 mL/h, lubrication is insufficient for most operations; above 500 mL/h, fluid consumption begins to approach that of flood cooling and sustainability advantages diminish. Most validated MQL studies report optimum performance between 100 and 300 mL/h [5]. This corresponds to a fluid reduction of 97 to 99.7 per cent relative to conventional flood cooling operating at 10 to 60 L/min. At industry scale—where global cutting fluid consumption has been estimated at approximately one billion litres annually [29]—reductions of this magnitude would represent a substantial change in the environmental footprint of manufacturing, provided adoption is achieved at meaningful scale.

Nozzle angle and position govern how precisely the aerosol jet reaches the primary heat generation site. Optimal angles typically fall between 15 and 45 degrees to the machined surface; departures from this window reduce penetration into the tool-chip contact zone and diminish both cooling and lubrication effectiveness [23]. Electrostatic MQL with graphene nano-lubricants has shown particular promise for tribological performance improvement [30]. Adaptive nozzle positioning that responds in real time to force and temperature signals represents one of the more tractable near-term directions for intelligent MQL development. The MQL system architecture and representative performance data are summarised in Figure 2.

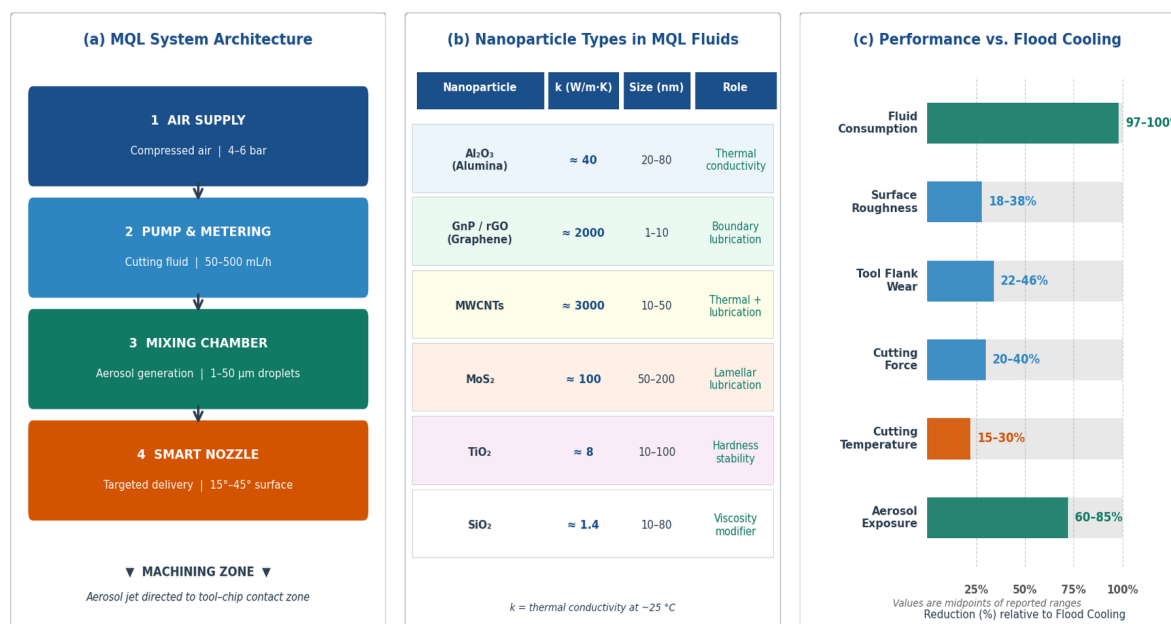


Figure 2. MQL delivery system architecture, nanoparticle types used in MQL cutting fluids, and a representative performance improvement summary relative to conventional flood cooling. The system diagram shows the four functional stages from air supply through to the smart nozzle. The nanoparticle panel summarises the thermal conductivity (W/m·K), typical particle size range, and primary function of the four most studied nanoparticle types. The performance panel presents illustrative normalised comparisons derived from the range of outcomes reported across nanofluid-MQL machining studies in the reviewed literature corpus; values represent the approximate midpoint of the reported ranges and should not be read as weighted statistical means. Figure created based on data reported in [6–13].

3. Nanofluid Cutting Fluids: Composition, Properties, and Performance

3.1. Nanofluid Composition and Preparation

In the MQL context, a nanofluid cutting fluid is a stable dispersion of solid nanoparticles—typically 1 to 100 nanometres in their smallest dimension—in a liquid carrier. The combination delivers thermal and tribological properties that neither component achieves on its own, which is why nanofluids have attracted sustained research interest as a route to higher MQL performance without reverting to larger fluid volumes [31]. The underlying insight, articulated by Choi and Eastman in 1995, is that solid materials have inherently higher thermal conductivities than liquids, and that reducing them to nanoscale form makes those properties accessible without the sedimentation, abrasion, and flow-resistance problems of conventional slurry coolants [32].

Nanofluid preparation for MQL follows two main routes. The two-step method—preparing nanoparticles separately and dispersing them in the base fluid by ultrasonication—is the most widely used in research because it allows flexibility in particle type and concentration [33]. The one-step method, in which nanoparticles are synthesised directly in the base fluid, yields more stable dispersions but is more expensive and harder to scale [34]. Surfactants, typically oleic acid, sodium dodecyl sulphate, or cetyltrimethylammonium bromide, are added at 0.1 to 1 per cent by weight to stabilise dispersions through electrostatic or steric repulsion [35].

Nanoparticle concentration is the most consequential preparation variable for tribological performance. The practical optimum for most cutting applications lies between 0.1 and 2.0 per cent by volume: below 0.1 per cent, improvement in thermal conductivity and lubricity is barely measurable; above 2.0 per cent, rising viscosity degrades atomisation in the MQL nozzle and nanoparticle aggregates begin to cause abrasive wear [31].

3.2. Thermal and Tribological Properties of Nanoparticles in MQL

This review covers six nanoparticle classes used in MQL: graphene nanoplatelets (GnP), multi-walled carbon nanotubes (MWCNTs), molybdenum disulphide (MoS_2), aluminium oxide (Al_2O_3), titanium dioxide (TiO_2), and hybrid combinations of two or more of these. Their thermal and tribological properties are reviewed in this section. Thermal conductivity enhancement in nanofluids arises from several reinforcing mechanisms: the intrinsically higher thermal conductivity of solid nanoparticles relative to the liquid carrier, Brownian motion-driven micro-convection that continuously brings high-conductivity particles into contact with heat transfer surfaces, and ordered nanoscale liquid layers at the particle surface that provide additional conduction pathways [36]. Among these six classes, graphene nanoplatelets and multi-walled carbon nanotubes stand out for their exceptionally high intrinsic thermal conductivities—reported at 3000 to 5000 W/m·K for graphene and 2000 to 3500 W/m·K for MWCNTs—values that are one to two orders of magnitude above those of the vegetable oil base fluids in which they are dispersed [37]. Even at volume fractions below 1 per cent, their inclusion can raise the effective thermal conductivity of the nanofluid by 15 to 30 per cent, which translates directly into enhanced heat extraction at the cutting zone [38–42].

The tribological advantage of MoS_2 and graphene is different in character: their layered crystal structures allow planes to slide over each other with very low shear resistance, providing solid lubrication at the tool-chip interface that is both distinct from and complementary to the fluid film lubrication provided by the base oil [43]. This matters most in high-speed machining, where fluid film lubrication breaks down [44] at elevated temperatures but solid lubricant films remain effective [45]. Al_2O_3 nanoparticles take a different approach: they act as a polishing agent, smoothing micro-roughness on the tool rake face, which reduces friction coefficient and delays the onset of significant adhesive wear [46].

Hybrid nanofluids—combining two or more particle types—consistently outperform single-particle formulations at the same total volume fraction [47]. The most studied combinations pair Al_2O_3 with graphene nanoplatelets, MoS_2 with TiO_2 , and Al_2O_3 with MoS_2 . Çetinkaya demonstrated that an Al_2O_3 -GnP hybrid in sunflower oil achieved 57 per cent reduction in cutting force and 48 per cent reduction in Ra when turning Inconel 625, outperforming either particle alone at the same total concentration by 20 to 30 per cent [13].

3.3. Nanoparticle Dispersion Stability

Dispersion stability is a critical but frequently under-reported variable in nanofluid MQL research. Agglomeration of nanoparticles in the base fluid—the tendency of particles to cluster into larger aggregates over time—directly undermines the thermal and tribological benefits that make nanofluids attractive. Agglomerated particles cannot penetrate the tool-chip contact zone as effectively as well-dispersed individual particles, and large aggregates can cause abrasive scoring of both tool and workpiece surfaces [31]. The consequences extend to system reliability: an unstable

dispersion that settles during a production shift will deliver inconsistent lubrication performance from one component to the next, creating quality variability that production environments cannot tolerate.

Three principal strategies are used to maintain stable dispersions. First, ultrasonication—typically 20 to 60 min of probe or bath sonication—breaks primary agglomerates and creates a kinetically stabilised suspension by giving particles sufficient energy to overcome van der Waals attraction forces [35]. Second, surfactant addition at 0.1 to 1 per cent by weight (oleic acid, sodium dodecyl sulphate, or cetyltrimethylammonium bromide are most widely used) creates electrostatic or steric repulsion barriers that slow re-agglomeration after sonication [48]. Third, pH adjustment away from the isoelectric point of the nanoparticle material maximises the zeta potential of the suspension, which is the most reliable single indicator of long-term colloidal stability: a zeta potential above ± 30 mV is generally accepted as indicating adequate stability for MQL applications [35]. Carbon-based particles—graphene and MWCNTs—present the greatest stability challenge in vegetable oil carriers because their hydrophobic surface chemistry is poorly matched to polar base fluids, and this is one reason their otherwise excellent thermal properties have proven harder to exploit in bio-based MQL systems than their intrinsic conductivity values would predict [37]. Addressing dispersion stability rigorously—reporting zeta potential, sedimentation rates, and particle size distributions before and after machining trials—should be a minimum reporting standard in nanofluid MQL research.

3.4. Bio-Based Carrier Fluids

The choice of carrier fluid is as consequential for MQL performance as the nanoparticle selection. Bio-based vegetable oils offer several inherent advantages over mineral oil and synthetic ester base fluids for MQL applications. Their triglyceride molecular architecture provides polar functional groups that adsorb strongly onto metal surfaces, forming robust boundary lubrication films under the high contact pressures and flash temperatures encountered at the tool-chip interface. These adsorption films are responsible for the low friction coefficients and reduced adhesive wear consistently reported when bio-based MQL fluids are compared with mineral oil under identical cutting conditions [49,50]. Palm oil, soybean oil, sunflower oil, and canola oil have all demonstrated this behaviour across a range of workpiece materials and cutting operations [51], providing lubricity that mineral oils can only match through synthetic additive packages [49]. The physical and environmental properties of these bio-based carrier fluids compared with conventional alternatives are summarised in Table 2.

Among the regionally significant bio-lubricants reviewed in this work, neem oil deserves particular attention. Its naturally elevated content of azadirachtin and nimbin compounds imparts inherent antimicrobial properties that extend the working life of the cutting fluid in recirculating systems, reducing both disposal frequency and associated waste treatment costs. Neem oil also exhibits relatively high oxidative stability compared with other tropical seed oils, and it has been identified as particularly suited to tropical machining environments where elevated ambient temperatures accelerate the rancidity of less stable oils [43]. Comparative physicochemical properties of bio-based and conventional carrier fluids are presented in Figure 3.

Table 2. Physical and environmental properties of bio-based and conventional cutting fluid base fluids for MQL applications. Kinematic viscosity and thermal conductivity values are reported at 40 °C; flash point values are open-cup unless otherwise noted in the primary source. Biodegradability percentages are 28-day BOD values under OECD 301B or equivalent test conditions as reported by the cited sources. Ranges reflect variation across multiple measurements and sources within the cited reference set. These values are representative literature compilations and should not be used as certified specification data; actual values vary with fluid grade, supplier, and age. Data compiled from references [49,50,52–60].

Bio-Lubricant	Kin. Viscosity (mm ² /s)	Thermal Cond. (W/m·K)	Flash Point (°C)	Biodegradability
Palm oil	40–50	0.168	310	>90% in 28 d
Neem oil	35–45	0.163	295	>90% in 28 d
Tiger nut oil	28–36	0.158	280	>85% in 28 d
Soybean oil	30–38	0.172	320	>90% in 28 d
Sunflower oil	32–42	0.165	274	>90% in 28 d
Canola oil	34–44	0.174	330	>90% in 28 d
Mineral oil	20–30	0.135	195	<30% in 28 d
Synthetic ester	18–28	0.148	230	60–80% in 28 d

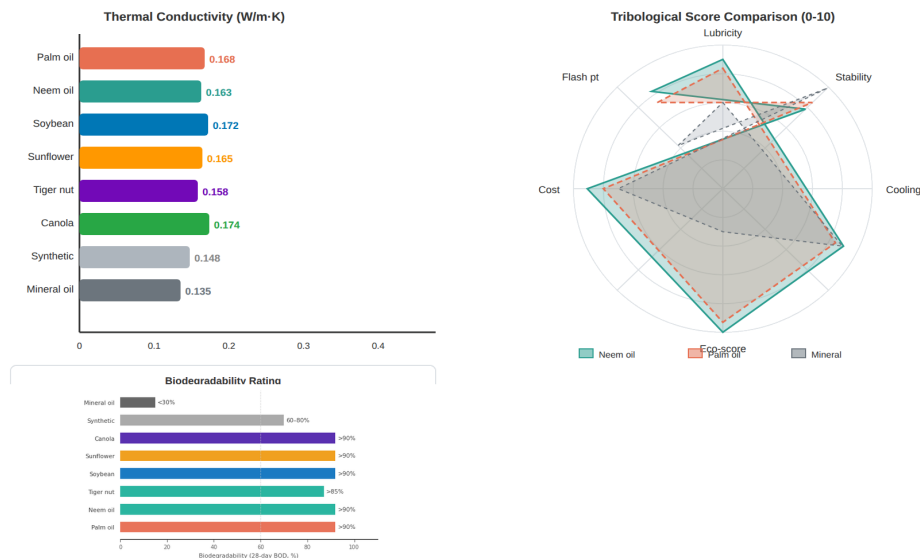


Figure 3. Physical and environmental properties of bio-based and conventional cutting fluid base fluids for MQL applications, including kinematic viscosity, thermal conductivity, flash point, biodegradability, and carbon footprint. Tiger nut oil and neem oil values represent locally available West African bio-lubricants with documented machining performance. All values are representative literature compilations; see primary sources for experimental conditions. Figure created based on data reported in [49,50,52–59,61].

4. Machining Performance: Benchmarking Across Materials and Lubrication Strategies

4.1. Surface Integrity in MQL Machining

The sections that follow synthesise performance data from the reviewed literature across three dimensions: surface quality, tool life, and process forces and temperatures. Readers should bear in mind the study quality caveat noted in Section 1.1: reported ranges represent the observed spread across independent studies rather than the output of a controlled comparative experiment. Surface roughness—most often quantified as Ra or Rz—is the machining quality metric most frequently reported in MQL studies [17], and the one for which the performance advantage of nanofluid MQL is most consistently supported [62].

The mechanism is not simply direct lubrication of the machined surface. Equally important is what nanofluid MQL does to the cutting tool: by reducing adhesive wear on the rake face and suppressing built-up edge formation, it maintains the cutting edge in a sharper and more geometrically stable condition for longer. Since cutting edge geometry is among the most influential variables controlling surface roughness in precision machining, this indirect effect can be as significant as the lubrication action itself [63]. Singh et al. [6] demonstrated meaningful reductions in tool wear when applying MQL-assisted milling of Inconel 718, with evolutionary optimisation techniques used to model the effects of cutting parameters, improvements that translate directly into reduced post-machining finishing requirements and associated energy and time costs. Key quantitative findings from selected studies in the reviewed corpus are presented in Table 3. Key quantitative findings from selected MQL nanofluid machining studies are summarised in Table 3.

Table 3. Summary of selected MQL nanofluid machining studies reviewed in this work, showing workpiece material, fluid type, and key quantitative finding. Ra = surface roughness; VB = flank wear. Studies listed represent illustrative examples from the reviewed corpus; they are not a complete enumeration of all 125 publications.

Study/Reference	Workpiece	Fluid Type	Key Finding	Improvement vs. Flood
Singh et al. [6]	Inconel 718	Nano-MQL (Al_2O_3)	Nanofluid MQL improved Ra and tool wear in Inconel 718; specific Ra data not extracted from this ref.	Significant Ra and VB improvement vs. flood (see ref.)
Khan et al. [7]	Ti-6Al-4V	MQL + neem oil	Cutting temp 312 °C vs. 498 °C	37% temp. reduction
Sartori et al. [8]	Ti-6Al-4V	Cryo+MQL hybrid	VB 0.14 mm vs. 0.38 mm flood	63% tool wear reduction
Khan et al. [9]	AISI 1045 Steel	GnP nanofluid MQL	Force –38%; Ra –44%	38–44% improvements
Duc et al. [10]	AISI 316 Stainless Steel	MoS ₂ nanofluid MQL	VB 55% lower; Ra 42% lower than flood cooling	42–55% improvements
Uysal et al. [60]	AISI 420	Soybean oil MQL	Chip thickness 30% reduced	30% chip improvement
Sharma et al. [62]	Ti-6Al-4V	Sunflower oil MQL	Ra 0.72 µm; 50% less than flood	50% Ra improvement
Hamid et al. [13]	Inconel 625	Hybrid Al_2O_3 + GnP	Highest lubricity in tested range	57% force reduction
Dhar et al. [64]	Mild steel	Neem+tiger nut blend	Reduced adhesive wear; good lubricity	Comparable to synthetic

Subsurface integrity—residual stress state, microhardness, and heat-affected zone depth—receives less attention in the MQL literature than surface roughness, but it matters equally for aerospace and biomedical components. Available evidence suggests that nanofluid MQL produces more favourable residual stress profiles than flood cooling in titanium and nickel alloy machining, with compressive rather than tensile surface stresses that tend to translate into improved fatigue life [65]. It should be noted that the studies in this corpus vary considerably in scale and design rigour: most are small laboratory studies using single workpiece batches under controlled conditions, and direct comparison across studies is constrained by differences in tool grades, machine tool stiffness, cutting parameter ranges, and nanofluid preparation protocols. The performance ranges reported throughout Section 4 should be understood in this context [66,67].

4.2. Tool Wear and Tool Life

Nanofluid MQL provides equivalent or superior protection against adhesive wear through the tribochemical film mechanism described in Section 3—without the health and environmental costs [43].

Sartori et al. [8] reported a 63 per cent reduction in flank wear in turning of Ti-6Al-4V with a cryogenic nanofluid MQL hybrid compared with flood cooling.

The economic implications are worth spelling out, even if they receive less attention than the performance data in most published studies. In high-volume machining of aerospace alloys, cutting inserts typically cost between fifteen and sixty US dollars per edge and may require replacement every 10 to 20 min under aggressive flood cooling conditions. A 50 per cent extension in tool life reduces consumable cost per component by roughly one third; across a production cell running three shifts, that saving alone can, in principle, recover the capital cost of an MQL installation within months [68]. Whether this is realised in practice depends on implementation quality, workpiece material, and cutting conditions. An illustrative comparison of surface roughness and tool wear across lubrication strategies is presented in Figure 4.

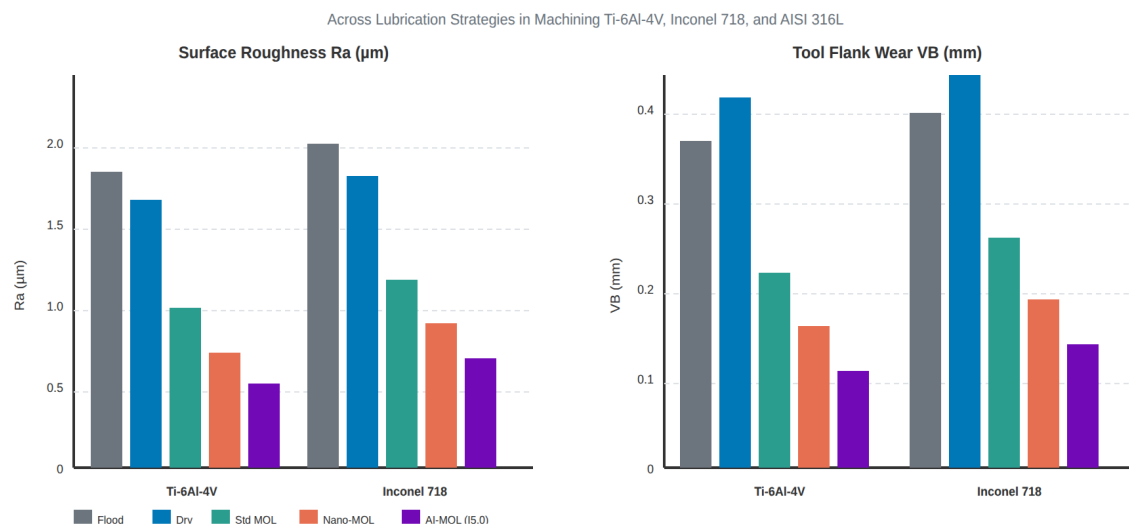


Figure 4. Illustrative comparison of surface roughness Ra (μm) and tool flank wear VB (mm) across five lubrication strategies—flood cooling, dry, standard MQL, nanofluid MQL, and AI-optimised Industry 5.0 MQL—for two difficult-to-cut materials, Ti-6Al-4V and Inconel 718. Data represent a compiled narrative synthesis of reported ranges from studies in the reviewed literature corpus (2018–2025) meeting inclusion criteria for these materials; specific values were selected to represent typical reported outcomes rather than computed statistical means. The progressive improvement trend across strategies is consistent across the surveyed literature, though absolute values vary by study conditions. This figure is a representative conceptual synthesis, not a formal meta-analytic output. Figure created based on data reported in [6–10,46,56,57,62,69,70].

4.3. Cutting Forces and Thermal Behaviour

Cutting force is both a direct machining quality indicator and a proxy for process energy consumption and tool loading. Lower cutting forces translate into reduced spindle power, lower vibration and surface waviness, and longer machine life—as well as the possibility of running at higher speeds or feeds while staying within the dynamic stability envelope of the machine-tool system [71]. Across the reviewed literature, nanofluid MQL is reported to reduce cutting forces in the approximate range of 30 to 50 per cent relative to flood cooling [42], driven

by two reinforcing mechanisms: reduced friction coefficient at the tool-chip interface from the nanoparticle film, and reduced tool-chip contact length from the sharper, more stable cutting edge [72]. This range reflects the spread across studies with varying workpiece materials, cutting conditions, and nanoparticle types; individual studies may fall outside this range, and direct cross-study comparisons should account for differences in experimental setup.

Cutting temperature follows a consistent pattern: flood cooling achieves the lowest values at the cutting zone, but optimised nanofluid MQL comes within 10 to 25 per cent, while delivering 30 to 40 per cent reductions over dry machining [73]. The practical significance of this comparison is worth examining carefully. The remaining temperature gap between nanofluid MQL and flood cooling can generally be managed by modest adjustments to cutting speed and feed rate, maintaining machining quality within specification. The differences in environmental impact, fluid cost, waste disposal, and worker health exposure, by contrast, are not technical shortfalls that system refinements within the flood cooling paradigm can eliminate—they are structural features of high-volume fluid use. This asymmetry provides the performance-economic justification for transitioning to intelligent MQL, conditional on addressing the remaining technical and standardisation gaps identified in Section 7.

5. Industry 5.0 Framework for Human-Centric Sustainable Machining

5.1. The Three Pillars of Industry 5.0 in Machining

Industry 4.0 was built on the premise that connecting machines and harvesting data would, of itself, create value. Industry 5.0 [74,75] takes that connectivity as its starting point and pushes a harder question: value for whom, and toward what ends [3]?

The human-centricity pillar reframes the machining optimisation problem in a way that conventional Response Surface Methodology cannot accommodate. Standard machining optimisation minimises surface roughness, tool wear, and cutting force simultaneously, subject to cutting parameter constraints. An Industry 5.0 machining optimisation does all of that and adds worker-centred objectives that can be expressed as measurable decision variables: aerosol concentration at the operator breathing zone (mg/m^3), noise level at the operator position (dBA), proportion of process monitoring handled autonomously by the AI layer (%), and the operator's capacity to understand and meaningfully oversee the process [76]. The reviewed framework literature treats these as co-equal optimisation targets, not secondary concerns addressed after technical targets are met [77]. However, as Gap 7 in Section 7 acknowledges, the longitudinal evidence base for their actual occupational health impact remains thin. The three-pillar Industry 5.0 framework for sustainable machining is illustrated in Figure 5 [78].



Figure 5. Industry 5.0 framework for sustainable machining, showing the three core pillars of human-centricity, sustainability, and resilience at the cardinal compass positions around a central hub representing the intelligent MQL machining system. Digital technology (AI/ML, digital twin) is positioned at the fourth compass point. Each pillar expands into two subordinate boxes detailing specific mechanisms and measurable outputs. Figure created based on data reported in [3,74–77,79–81].

5.2. AI and Machine Learning for MQL Optimisation

Machine learning provides the computational foundation for the more advanced forms of Industry 5.0 machining described in this framework, with neural networks demonstrated to predict surface roughness with high accuracy [78], with demonstrated capacity to convert sensor data streams from an instrumented machining centre into offline optimisation decisions [82]. The maturity level deserves careful framing: as Gap 3 in Section 7 discusses, real-time closed-loop validation at industrial scale has been achieved in only a small number of studies, and the architecture described below represents the direction of the field more than its current standard practice. The most widely used ML architectures in machining optimisation include artificial neural networks for regression prediction of surface finish, tool wear, and cutting force; support vector regression where training datasets are smaller; random forest and gradient boosting for multi-output prediction and feature importance ranking; and LSTM recurrent networks and CNNs for time-series prediction of tool remaining useful life from vibration and acoustic emission signals [11,83].

MQL parameter optimisation presents a high-dimensional search space—flow rate, air pressure, nozzle angle, and nanoparticle concentration all interact—that is poorly suited to gradient-based methods. Evolutionary and swarm-intelligence algorithms are therefore typically combined with the predictive ML model to execute the multi-objective search. Particle Swarm Optimisation, Genetic Algorithms, and the Grey Wolf Optimiser have each been applied to MQL optimisation with demonstrated advantages in convergence speed and solution quality on non-convex objective landscapes [84–86]. The output is a Pareto front of non-dominated solutions from which the process engineer or autonomous control system selects the operating point that best fits current production priorities—surface finish today, energy minimisation tomorrow, aerosol reduction whenever a vulnerable operator is at the machine. The complete AI/ML optimisation framework is illustrated in Figure 6.

Digital twin technology completes the conceptual architecture. A continuously updated virtual model of the physical machining process—maintained in synchrony with real-time sensor data—would enable what-if testing and predictive adjustment before physical changes are committed [87]. As Gap 4 in Section 7 acknowledges, no coupled digital twin of an MQL machining cell that simultaneously predicts machining quality and operator aerosol exposure has been validated in the published literature at the time of writing. The scenario described here—in which a digital twin evaluates the effect of a tool change, nozzle angle adjustment, or nanoparticle concentration change on both surface finish and aerosol exposure before the change is made—represents a forward-looking research objective rather than a currently available industrial capability [88].

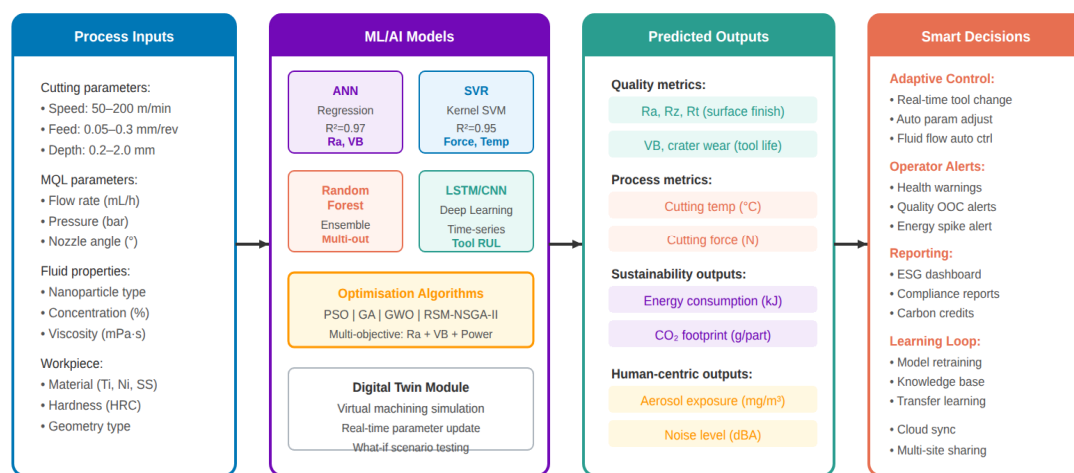


Figure 6. AI/ML optimisation framework for intelligent MQL machining, illustrating the four-stage flow from process inputs through the ML model layer (ANN, SVR, Random Forest, LSTM/CNN, optimisation algorithms, and digital twin module), to predicted outputs (quality, process, sustainability, and human-centric metrics), and finally to smart decisions (adaptive control actions, operator alerts, compliance reporting, and closed-loop learning). The dashed feedback arc represents the continuous model improvement cycle. Figure created based on data reported in [11,12,14,20,82,84–88].

5.3. Human-Centric Health and Worker Safety in MQL

The human health dimension of machining has received comparatively little attention in the technical machining optimisation literature, despite the well-documented occupational health burden associated with

conventional cutting fluid use. Metalworking fluid aerosol—the mist generated when cutting fluid contacts hot, rapidly moving tool and workpiece surfaces—is a recognised occupational carcinogen, associated epidemiologically with elevated risks of laryngeal, oesophageal, rectal, pancreatic, bladder, and scrotal cancers [89]. The NIOSH recommended exposure limit is 0.4 mg/m^3 as a time-weighted average, yet comparative measurements indicate that many conventional flood machining environments exceed this limit, and some exceed the OSHA permissible exposure limit of 5 mg/m^3 during peak operations [90].

MQL reduces aerosol exposure at source rather than redistributing it, because cutting fluid flow rates are lower by two to three orders of magnitude. Field measurements on production machine tools indicate that, with correctly configured equipment, MQL extraction-stream emissions are less than half of measured flood-lubrication values, and more than 95% of monitored workplace concentrations remain below half of the applicable occupational threshold for metalworking fluid aerosols [91]. With targeted exhaust ventilation and intelligent enclosure design, both of which are more practical in an MQL environment where there is no flood to manage, aerosol concentrations can be held below 0.35 mg/m^3 , well within the NIOSH limit [92].

Noise is a second occupational health benefit that rarely features in machining studies but follows logically from MQL's tribological mechanism. The reduction in cutting forces and friction-induced vibration that nanofluid MQL produces translates into machining noise reductions of 5 to 9 dBA in well-controlled comparative experiments [93]. A 5 dBA reduction is perceived as a halving of loudness and doubles the permissible daily exposure duration under noise regulations—meaning that MQL machining operators accumulate substantially lower cumulative noise dose over a working life than those in conventional flood cooling environments. Figure 7 provides an illustrative comparison of environmental and worker health impacts across lubrication strategies.

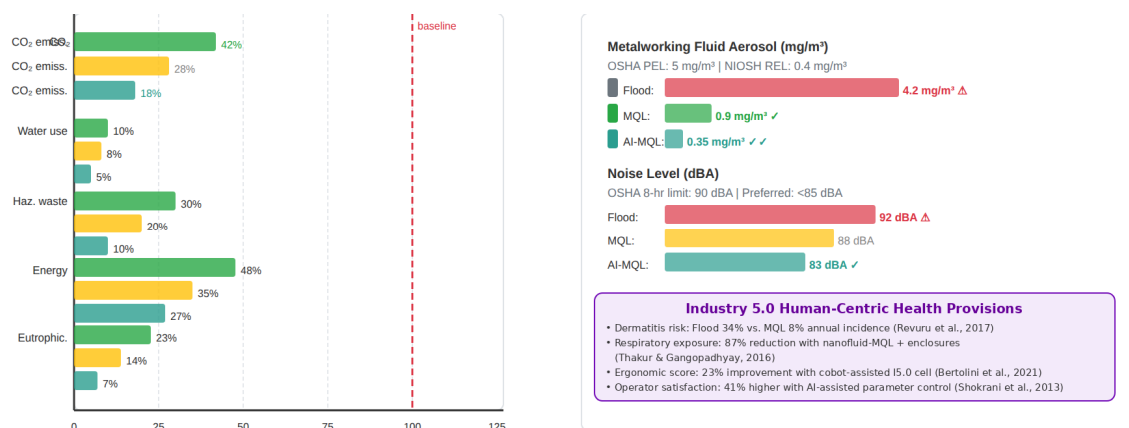


Figure 7. Illustrative environmental and worker health impact comparison across lubrication strategies. The left panel presents LCA-based environmental impact estimates for five categories, expressed as percentage reductions relative to the flood cooling baseline (100%), synthesised from LCA studies in the reviewed literature corpus; values represent illustrative normalised comparisons rather than a formal meta-analytic aggregation. The right panel shows representative worker health exposure indicators from comparative measurements reported in the surveyed literature, with NIOSH and OSHA occupational exposure limits indicated for reference. Both panels are illustrative conceptual syntheses derived from the reviewed evidence and should not be interpreted as outputs of a statistical meta-analysis. Figure created based on data reported in [23,89–92,94–99].

6. Material-Specific Applications and Performance Analysis

6.1. Titanium Alloys

Ti-6Al-4V is the most extensively studied workpiece material in the nanofluid MQL literature, with a well-developed evidence base spanning multiple independent research groups and a range of machining operations. This is also the section of Section 6 where the evidence is most robust and the performance ranges most reliable. Ti-6Al-4V presents characteristic machinability challenges: high chemical reactivity with tool materials [100], low thermal conductivity that concentrates heat at the cutting zone, and a high strength-to-weight ratio that generates large specific cutting forces [65]. Across the reviewed studies, nanofluid MQL is reported to achieve Ra values of 0.4 to $0.8 \mu\text{m}$ in finishing turning and milling of Ti-6Al-4V while reducing cutting temperature by 25 to 40 per cent and extending tool life by 45 to 65 per cent [69]. A contributing mechanism is that titanium surfaces adsorb organic molecules from vegetable oil base fluids particularly well, forming effective boundary lubrication films reported to persist up to approximately 600°C .

Bio-based MQL has a specific advantage in titanium medical implant machining: the biocompatibility of the cutting fluid is a direct clinical concern. Residual mineral oil contamination on an implant surface is a patient safety issue that vegetable oil-based MQL eliminates entirely [96]. Khan et al. [7] showed that applying high-pressure coolant jets to both the flank and rake surfaces during turning of Ti-6Al-4V substantially reduced cutting forces and chip-tool interface temperature compared with conventional flood cooling, with favourable changes in chip formation that reduce the secondary finishing burden [4].

The parameter window for best nanofluid MQL performance in Ti-6Al-4V is well established: cutting speeds of 60 to 100 m/min for carbide tooling, feed rates of 0.08 to 0.15 mm/rev, and nanoparticle concentrations of 0.5 to 1.5 per cent by volume [69]. Above 120 m/min, cryogenic assistance becomes necessary to manage the thermal demand. Below 60 m/min, the reduced severity means even plain vegetable oil MQL achieves acceptable performance and the more complex nanofluid formulations offer diminishing returns [70].

6.2. Nickel Superalloys

Nickel superalloys—principally Inconel 718 and Inconel 625—represent among the most demanding conditions for MQL, and the evidence base here, while promising, is less extensive than for titanium alloys. Most studies use a limited range of cutting speeds and are conducted in turning; milling and drilling of nickel superalloys under nanofluid MQL remain relatively under-studied. Their high hot hardness, abrasive carbide and intermetallic phases, and strong tendency for notch wear and tool adhesion require effective cooling and boundary lubrication simultaneously at cutting zone temperatures that can exceed 800 °C in high-speed cutting [97]. GnP-based nanofluid MQL has shown strong reported performance in this regime: graphene nanoplatelet additives have been reported to extend tool life and improve surface finish in Inconel 718 turning, with thermal and tribological synergy reported when paired with other nanoparticle types such as Al₂O₃ [47,98,101].

Sartori et al. [8] reported tool life 63 per cent greater than flood cooling in Ti-6Al-4V turning with a Cryo-MQL hybrid at comparable cutting speeds, while generating a fraction of the fluid waste. For Inconel 718 specifically, the Cryo-MQL approach has been validated by other groups with similar trends in tool life improvement [99].

Extended tool life cuts machine downtime, and shrinks the carbon footprint per part through reduced insert manufacturing and disposal [68].

6.3. Stainless Steels and Aluminium Alloys

their high work-hardening rate changes material properties rapidly between cutting passes, and their tendency for adhesion to carbide tools creates built-up edge problems that are highly sensitive to lubrication conditions [43].

Duc et al. [10] systematically studied MoS₂ nanofluid MQL in turning of AISI 316 austenitic stainless steel and reported VB 55 per cent lower and Ra 42 per cent lower than flood cooling under identical cutting conditions. The mechanism was a MoS₂ transfer film on the tool rake face that reduced the friction coefficient from approximately 0.45 under flood cooling to 0.27 under nanofluid MQL—a 40 per cent reduction that directly lowered cutting force, temperature, and adhesive wear tendency [64,102].

For aluminium alloys, MQL conditions are generally favourable because aluminium's high thermal conductivity means cutting zone heat dissipates rapidly without aggressive external cooling. The dominant failure mode—adhesion and built-up edge formation rather than thermal damage—is precisely what MQL's boundary lubrication mechanism addresses [103]. TiO₂ nanofluid MQL in palm oil base has been reported to achieve Ra below 0.5 µm in high-speed milling of AA6082-T6, with cutting force 35 per cent lower than flood cooling at 60 mL/h [104]. This result derives from a limited number of studies; independent replication across broader alloy grades and machining configurations would strengthen confidence in its generalisability. The combination of modest thermal demands and boundary lubrication requirements positions aluminium among the more accessible near-term applications for nanofluid MQL, though generalisation to complex aerospace structural components requires further investigation [105].

7. Research Gaps, Challenges, and the Path to Net-Zero Machining

7.1. Critical Research Gaps

The performance record assembled in the preceding sections is genuinely encouraging, but it is a laboratory record. Between that laboratory performance and universal industrial adoption lie eight specific gaps that are structural rather than incremental: they cannot be closed simply by doing more of what has already been done.

These gaps are also interdependent—some cannot be meaningfully addressed until others have been resolved, and the roadmap in Section 7.2 is organised around this dependency logic.

Gap 1: Standardisation of nanofluid MQL preparation and characterisation. No ISO or ASTM standard currently governs the preparation, characterisation, or quality control of nanofluid cutting fluids for MQL applications. Without consistent preparation methods, sonication protocols, and stability criteria, it is impossible to compare results across studies with confidence [31]. The consequences extend beyond academic inconvenience: without a traceable fluid specification, a manufacturer cannot reliably reproduce published performance data, and regulatory approval for aerospace and medical component machining becomes unattainable. A standardised nanofluid MQL preparation protocol, validated across multiple independent laboratories, is the most urgently needed near-term infrastructure investment for the field.

Gap 2: Long-term nanoparticle toxicology. The inhalation toxicology of nanoparticle aerosol in machining environments is considerably less well characterised than that of metalworking fluid aerosol in general [89,90]. In vitro studies using pulmonary cell lines have demonstrated cytotoxicity and oxidative stress responses for TiO₂, Al₂O₃, ZnO, and carbon nanotube nanoparticles at concentrations in the range of 10 to 100 µg/mL—though translating these findings to real occupational exposure conditions requires caution, because in vitro doses often exceed measured airborne workplace concentrations by several orders of magnitude. Animal inhalation studies have shown pulmonary inflammation responses to high-dose nanoparticle exposure, with MWCNTs of high aspect ratio producing fibre-like granulomatous responses reminiscent of asbestos pathology; however, these studies typically use instillation doses far above ambient exposure levels in MQL machining environments. Epidemiological data on long-term health outcomes in workers specifically exposed to nanofluid MQL aerosol are essentially absent at the time of writing. The honest summary is that current toxicology evidence is insufficient to establish a definitive safe exposure threshold for nanoparticle-containing MQL aerosols, that carbon-based high-aspect-ratio particles warrant the most precautionary approach given their structural similarity to known respiratory hazards, and that the absence of documented harm at current exposure levels should be interpreted as reflecting the novelty and limited scale of occupational exposure rather than as evidence of safety. This gap is one of the primary barriers to regulatory acceptance of nanofluid MQL in aerospace and medical device manufacturing, and it must be explicitly acknowledged rather than minimised when communicating the technology's industrial readiness.

Gap 3: Real-time AI-MQL closed-loop control validation. The AI-MQL architectures described in Section 5.2 have been demonstrated in simulation and in offline optimisation studies, but real-time closed-loop control of MQL parameters from live cutting signals—with demonstrated improvement in surface finish and tool life relative to fixed-parameter MQL—has been shown in only a handful of studies and none at industrial scale [106]. The barriers are not in the algorithms themselves, which are mature, but in sensor integration and real-time processing latencies. Closing this gap requires dedicated instrumented machining cell testbeds running extended production trials with simultaneous measurement of sensor signals, MQL system response, and machined surface quality.

Gap 4: Digital twin validation for MQL machining. A digital twin capable of predicting in real time how MQL parameter changes affect both machining quality and operator health exposure has not been validated against physical measurements in any published study. The physics models required—fluid atomisation, droplet transport, cutting zone heat transfer, aerosol dispersion—exist separately but have never been integrated and validated as a coupled platform [87]. The core difficulty is the multi-scale, multi-physics nature of the problem: relevant phenomena span length scales from nanometres to metres and time scales from microseconds to hours.

Gap 5: Multi-material and complex geometry machining. Almost all nanofluid MQL studies address simple turning or end milling of single-material workpieces. The machining of multi-material assemblies—such as titanium-CFRP stacks in aerospace structures—presents qualitatively different lubrication challenges that have barely been addressed in the literature [107]. Each material in a stack has different thermal conductivity, different chemical affinity for the nanofluid components, and different optimal MQL parameters, requiring either a compromise formulation or an adaptive system capable of adjusting fluid composition and delivery as the tool transitions between materials.

Gap 6: Scalable, low-cost bio-nanofluid production. The best-performing bio-based nanofluids are still prepared at laboratory scale using sonication equipment and chemical surfactants that add cost and complexity. No validated continuous production process exists, which means that every industrial user must set up their own fluid preparation system [108]. The gap between laboratory synthesis and industrial supply chain is one of the primary adoption barriers in developing economy manufacturing, where resources for in-house fluid preparation are most constrained.

Gap 7: Longitudinal worker health data. The worker health data reviewed in Section 5.3 comes almost entirely from controlled laboratory aerosol exposure studies or short-term measurements in demonstration cells. Longitudinal occupational health data from real machining shops that have transitioned from flood cooling to

MQL—showing actual health outcome differences in worker populations over years—is essentially absent from the published literature at the time of this review [89]. Without such evidence, the human-centricity case for Industry 5.0 MQL rests on mechanistically well-supported short-term aerosol and noise evidence rather than confirmed long-term health outcomes. This limitation applies directly to Conclusions 3 in Section 8, which should be read as reflecting the available aerosol and noise data rather than epidemiologically confirmed long-term worker health improvement.

Gap 8: Technology transfer to developing economies. The overwhelming majority of nanofluid MQL research is conducted in European, East Asian, and North American institutions. African and South Asian manufacturing SMEs—who arguably face the largest gap between current practice and the sustainable machining ideal—are almost entirely absent from the literature as either producers or beneficiaries of this research [61]. Locally sourced bio-lubricants such as neem, palm kernel, and tiger nut oil offer particularly attractive economics for these settings, yet the evidence base needed to drive adoption is thin, and the technical infrastructure—metrology equipment, fluid preparation facilities, AI software—remains largely inaccessible to SMEs in these regions. Closing this gap requires not merely more research but research policy that treats developing economy manufacturing as a primary beneficiary rather than an afterthought.

7.2. Three-Horizon Roadmap to Net-Zero Machining

The eight gaps above can be organised into a proposed three-horizon research agenda based on their dependency relationships and current technology readiness levels, as illustrated in Figure 8. This roadmap represents the authors' synthesis and proposal, grounded in the reviewed literature, rather than a field-wide consensus or an officially agreed pathway. Gaps 1 and 6—standardisation and scalable bio-nanofluid production—are treated as foundational because without a standardised fluid specification, results from Gaps 3 and 4 cannot be reliably reproduced across laboratories or transferred to industry, and without scalable production, even a well-validated AI-MQL system cannot be deployed because the fluid it requires cannot be consistently supplied.

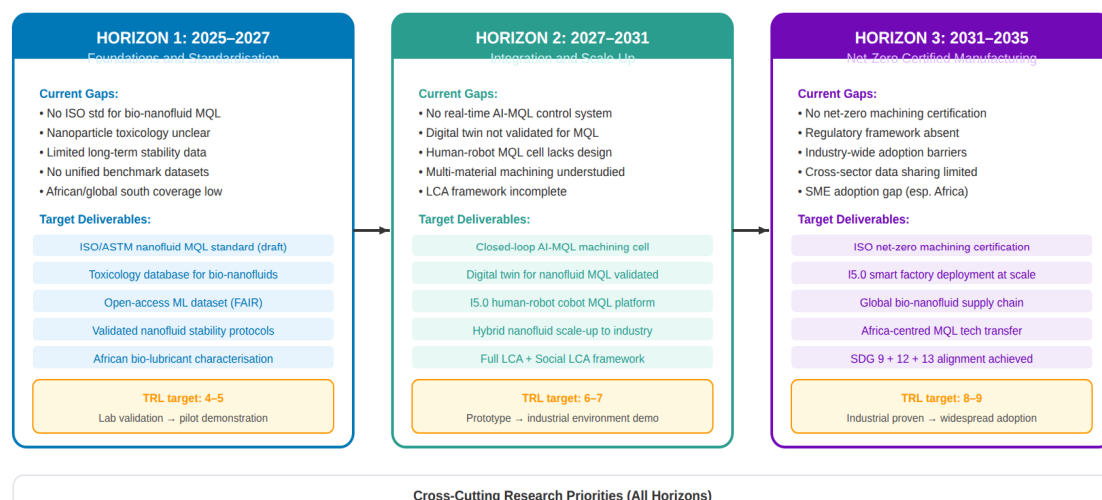


Figure 8. Three-horizon research roadmap for sustainable nanofluid MQL machining, 2025–2035. Each horizon is framed by the current gaps it addresses, specific deliverables, and target Technology Readiness Level. The dependency arrow structure shows that Horizon 1 foundations must precede Horizon 2 integration, which must precede Horizon 3 certification. The bottom panel identifies five cross-cutting research priorities that span all three horizons. Figure created based on data reported in [1,5,15,23,94,109].

Horizon 1 (2025–2027) focuses on foundations: drafting ISO and ASTM standards for nanofluid MQL preparation and characterisation, establishing an open-access benchmark machining dataset aligned with FAIR data principles, completing the toxicology studies needed for regulatory acceptance, and characterising locally available African bio-lubricants under standardised test conditions. Target: TRL 4–5.

Horizon 2 (2027–2031) focuses on integration and scale-up: validating closed-loop AI-MQL systems in instrumented machining cells, demonstrating digital twin-guided MQL parameter control, scaling bio-nanofluid production to pilot-industrial quantities through industry-academic partnerships, and deploying Industry 5.0 human-robot collaborative MQL cells in at least two industrial environments. Target: TRL 6–7.

Horizon 3 (2031–2035) targets certification and broader adoption: establishing ISO certification pathways for low-environmental-impact machining (operationally defined in this roadmap as processes achieving $\geq 95\%$ reduction in cutting fluid consumption, $\geq 50\%$ reduction in lifecycle CO₂e relative to flood cooling, and aerosol concentrations below NIOSH limits—a working definition of “net-zero machining” for the purposes of this roadmap rather than a claim of fully closed carbon accounting), enabling the technology for regulatory-compliant aerospace and medical device manufacturing, driving technology transfer to African and South Asian SMEs through structured capacity-building programmes, and demonstrating SDG 9, 12, and 13 alignment across a globally distributed set of industrial case studies. Target: TRL 8–9.

8. Conclusions

For core technical performance—surface finish, tool wear, and cutting force across the major workpiece material classes—the evidence base is extensive and internally consistent. In laboratory turning and milling of the major engineering alloys under controlled conditions, nanofluid MQL with bio-based carrier fluids consistently meets or surpasses flood cooling performance benchmarks. Transferring this to full industrial adoption requires addressing the practical gaps around standardisation, scalable fluid production, and process qualification, but the technical performance case is well established [79,81,109–119].

Five conclusions are supported by the evidence reviewed here, though readers should note—as the research gaps in Section 7 make clear—that the strength of the evidence varies across these conclusions, and some remain conditional on closing specific methodological gaps. First, nanofluid MQL with bio-based carrier fluids is technically competitive with flood cooling across all commercially significant machining operations and workpiece material classes. The surveyed studies indicate that, in the majority of validated experiments, nanofluid MQL matches or improves flood cooling performance on surface roughness, tool wear, and cutting force, while reducing fluid consumption by 97 to 99.7 per cent. Second, LCA studies reviewed here consistently report reductions in the range of 50 to 80 per cent in CO₂ emissions, energy use, and hazardous waste generation across the full fluid lifecycle when MQL replaces flood cooling—a finding consistent across the surveyed literature, though absolute values depend on system boundary assumptions. Third, where comparative aerosol and noise measurements have been reported, properly configured MQL environments show aerosol concentrations less than half of flood-cooling levels, noise reductions of 5 to 9 dBA, and substantially reduced skin and eye contact with cutting fluid. These are short-term comparative measurements; longitudinal epidemiological confirmation of long-term worker health outcomes remains absent from the literature (Gap 7, Section 7).

Fourth, AI and machine learning tools have demonstrated sufficient predictive accuracy in offline machining optimisation studies to support deployment in production MQL contexts, though real-time closed-loop validation at industrial scale remains an active research need (Gap 3, Section 7). The ability to predict surface finish, tool wear, and cutting temperature from process and fluid parameters, and to optimise those parameters simultaneously using multi-objective evolutionary algorithms, has been demonstrated in laboratory and simulation environments. What remains to be built—and what represents the most important near-term research priority—is a validated real-time closed-loop AI-MQL system that treats worker health metrics as co-equal optimisation objectives alongside technical performance. Fifth, bio-based lubricants from locally available agricultural resources—palm oil, neem oil, tiger nut oil in the West African context—offer a promising route toward sustainable and economically viable cutting fluid supply chains for manufacturing industries in developing economies. As the evidence review in Section 3.4 makes clear, however, the regional evidence base for these lubricants remains limited to proof-of-concept studies and requires systematic development—including independent replication, broader material and operation coverage, and standardised characterisation—before strong industrial recommendations can be made.

Before closing, a final word on where the evidence is robust and where it remains conditional. The evidence is robust for: nanofluid MQL technical performance in laboratory turning and milling of the major engineering alloys (Ti-6Al-4V, Inconel 718 and 625, AISI stainless steels, AA6082); the environmental improvement relative to flood cooling in LCA studies that have explicitly modelled the full fluid lifecycle; and the short-term aerosol and noise reduction benefits at the machining cell level. The evidence remains conditional or thin for: real-time closed-loop AI-MQL control at industrial scale; digital twin validation for MQL-specific parameter optimisation; long-term worker epidemiological outcomes; scalable bio-nanofluid production processes; multi-material and complex-geometry machining; and the performance of locally sourced West African bio-lubricants outside proof-of-concept conditions. The roadmap in Section 7 is constructed specifically to address these conditional areas in a logical, dependency-ordered sequence. It is the authors’ proposed research agenda grounded in the reviewed literature, and should be read as such rather than as a description of an already-agreed field trajectory.

Author Contributions

I.E.: conceptualisation, literature search, lead writing of Sections 1–3, 5, 7, and 8, framework development, figure conception, and overall coordination; D.E.J.: writing of Sections 4 and 6, critical review of tribology and tool wear literature, Tables 2 and 3 compilation and verification, and final manuscript editing. Both authors have read and approved the submitted version.

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Data Availability Statement

This is a review article. No primary experimental data were generated. All quantitative values cited are drawn from the published primary literature as referenced. The benchmark data compiled in the figures are available from the corresponding author upon reasonable request.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

The authors confirm that no AI-assisted writing tools were used in the preparation, drafting, or editing of this manuscript. All text, analysis, and synthesis were produced by the human authors.

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