

Glycerol in the Industrial Metalworking: A Critical Narrative Review of Benefits, Limitations, and Application Range for Waste Management and Sustainability

By Luka Latinović¹, Smilja Marković², Vladimir Tomašević³, Jelena Raut⁴,

ABSTRACT:

The global oversupply of glycerol from biodiesel production has prompted interest in its industrial valorisation. One emerging pathway is its use as a base fluid for metalworking, where both the spent fluid and the swarf would avoid hazardous-waste classification, while also lowering worker exposure compared with petroleum-based emulsions. This review synthesises academic and industrial evidence to critically assess glycerol's potential through the combined lenses of tribology, thermal stability, occupational and environmental implications, and industrial feasibility. Available evidence indicates that glycerol offers biodegradability, non-toxicity, and boundary-lubrication capability, enabling metallic residues to be reclassified as recyclable rather than hazardous. However, neat glycerol undergoes viscosity loss and oxidative degradation above ~180–210 °C, with potential acrolein formation, restricting applicability to low-to-moderate temperature machining and selected carbide finishing. Sector-level analysis delineates feasible adoption windows across small/medium workshops, automotive finishing lines, heavy-machinery/shipbuilding cells, and limited aerospace applications. Glycerol therefore cannot be regarded as a universal substitute but as a selective, sustainability-oriented fluid whose industrial feasibility depends on thermal management, formulation control, and regulatory alignment. Within its defined application range, glycerol may support circular metalworking and waste-valorisation strategies where process conditions remain compatible with its limits.

Keywords: glycerol, metalworking fluids, industrial waste management, thermal stability, corrosion resistance, circular economy

1. Introduction

The growing emphasis on sustainability in industrial production has intensified the search for alternatives to conventional petroleum-based resources. One of the most pressing challenges lies in the sustainable management of by-products from renewable energy systems (J. T. Fernando & Siani, 2016), more particularly glycerol, which is generated in substantial quantities as a side product of biodiesel manufacturing (Monteiro et al., 2018; Latinović et al., 2020). It is estimated that glycerol accounts for approximately 10% of the total output of biodiesel transesterification processes, creating a global

¹School of Engineering Management, University “Union – Nikola Tesla”, Belgrade, Serbia

²Institute of Technical Sciences of Serbian Academy of Sciences and Arts

³School of Engineering Management, University “Union – Nikola Tesla”, Belgrade, Serbia

⁴School of Engineering Management, University “Union – Nikola Tesla”, Belgrade, Serbia

oversupply that depresses market value and raises questions regarding sustainable disposal or reuse pathways (Y. Liu *et al.*, 2022).

At the same time, the metalworking industry represents a critical node of global manufacturing, responsible for producing essential components across automotive, aerospace, construction, and heavy machinery sectors (Oxford Economics, 2019). One of the cornerstones of this industry is the use of metalworking fluids (MWFs), which serve vital functions in cooling, lubrication, chip evacuation, and surface finish quality (Pape *et al.*, 2023). However, conventional MWFs—largely based on mineral oils and synthetic additives—present severe environmental and occupational challenges (W. L. R. Fernando *et al.*, 2021; Pape *et al.*, 2023). Contamination of metallic swarf with biocidal emulsions often leads to its classification as hazardous waste, significantly increasing disposal costs and preventing straightforward recycling (Di Martino, 2021). Additionally, worker exposure to petroleum fractions, and biocides has been linked to carcinogenic diseases, respiratory diseases, skin disorders, and other health problems (Latinović & Marjanović, 2021). In this context, glycerol emerges as a candidate that connects two industrial sustainability agendas: the valorisation of renewable energy by-products, and the reduction of hazardous waste streams in manufacturing (Figure 1).

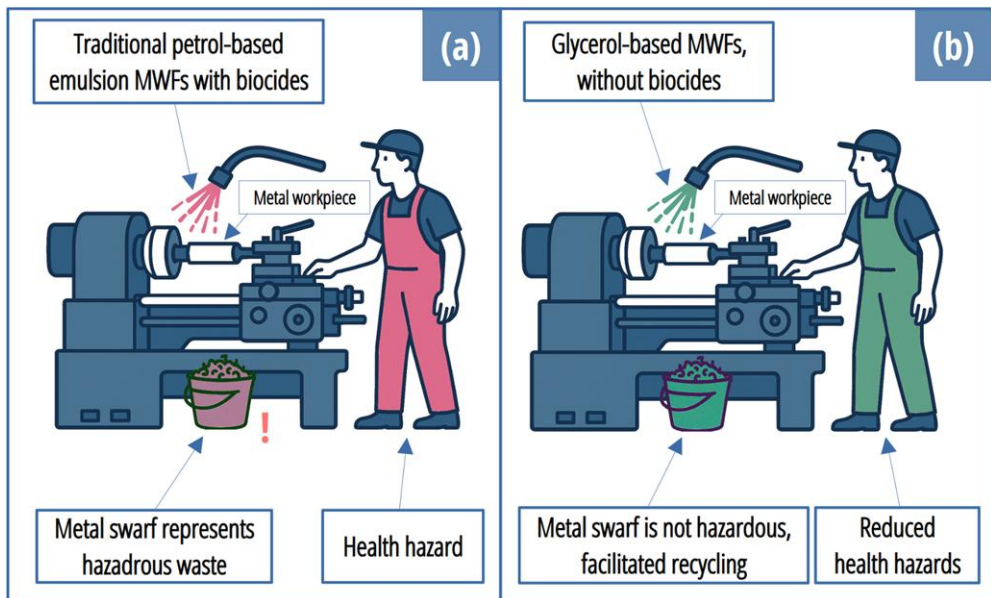


Figure 1. Comparison between metalworking flows with conventional petrol-based emulsion MWFs with biocides (a), and glycerol-based MWFs without biocides (b). Figure created by the authors.

Its intrinsic properties—biodegradability, biostatic properties (Winter *et al.*, 2012; Wichmann *et al.*, 2013), non-toxicity, and lubricity (Ma *et al.*, 2021) under boundary conditions—suggest the potential to function as a sustainable base fluid for MWF formulations. By replacing or supplementing conventional fluids with glycerol, industries could potentially achieve a triple sustainability gain:

1. Waste valorisation – transforming an oversupplied by-product into a productive industrial input;
2. Occupational safety – reducing exposure to hazardous additives;
3. Circular economy integration – enabling reclassification of machining residues from hazardous waste into recyclable secondary raw materials.

Despite these promising features, important questions remain. Glycerol suffers from thermal instability (Zhang et al., 2021), particularly under the high temperatures typical of advanced machining operations, where it may degrade and release harmful compounds such as acrolein (Belousov, 2021). Furthermore, variability in the purity of crude glycerol complicates its industrial adoption (Attarbach et al., 2023). The central question, therefore, is not whether glycerol can replace conventional fluids universally, but under what conditions and within what application ranges it may be realistically deployed as part of a sustainable industrial system.

This review critically examines the role of glycerol in the industrial metalworking sector, with a particular focus on sustainability outcomes. By synthesising available evidence on its benefits and limitations, the study defines an application range where glycerol can deliver tangible environmental, occupational, and economic value. The paper contributes to the broader debate on sustainable manufacturing by positioning glycerol not as a universal solution, but as a targeted enabler of circular economy practices in specific machining contexts.

2. Theoretical Background

Glycerol, also known as glycerine, is a trihydroxy alcohol that has long been utilised in sectors such as pharmaceuticals, cosmetics, food production, and chemical synthesis. Its global production has expanded dramatically over the past two decades largely as a consequence of the rapid growth of biodiesel manufacturing (Figure 2). Since glycerol constitutes roughly 10% of biodiesel transesterification output, the accelerated adoption of biodiesel has generated an oversupply in global markets that exceeds the demand, leading to frequent classification of crude glycerol as a low-value residual stream (Y. Liu et al., 2022). In many instances, it is co-incinerated for energy recovery, often without any attempt at upstream purification or functional recovery (Katryniok et al., 2009; Tomatis et al., 2024). This surplus has depressed prices, diminished its economic value (Table 1), and created an urgent need for valorisation strategies that can both absorb excess volumes and contribute to sustainability objectives (Moklis et al., 2023). At the same time, MWFs present a parallel sustainability challenge within manufacturing. Traditionally composed of petroleum-based oils and chemical additives such as emulsifiers, corrosion inhibitors, and biocides, MWFs play a critical role in reducing friction, dissipating heat, and extending tool life in machining operations (Latinović & Marjanović, 2021; Yurtkuran et al., 2024). Yet their widespread use has raised significant environmental and occupational concerns. Waste streams contaminated with biocidal emulsions are frequently classified as hazardous waste streams, requiring costly treatment and preventing straightforward recycling (Koch, 2023).

Table 1: Levels and key categories for change factors towards sustainability at the example of hospitals' secondary processes

Year	Total glycerol production (Mt)/price (USD/t)	Technical glycerol average price (USD/t)	Source for production	Source for price	Share from traditional sources / biodiesel
2003	~1.6	~900	(OECD & Food and Agriculture Organization of the United Nations, 2013; Ciriminna et al., 2014)	(Johnston & Holloway, 2007; Kenar, 2007; Ciriminna et al., 2014)	~88%/~12%
2005	~2	~950	(OECD & Food and Agriculture Organization of the United Nations, 2013; Ciriminna et al., 2014)	(Johnston & Holloway, 2007; Kenar, 2007; Ciriminna et al., 2014)	~70%/~30%
2007	~2.7	~970	(OECD & Food and Agriculture Organization of the United Nations, 2013)	(OECD & Food and Agriculture Organization of the United Nations, 2013)	~48%/~52%
2009	~3.2	~950	(OECD & Food and Agriculture Organization of the United Nations, 2013; Ciriminna et al., 2014; Ruy et al., 2020)	(OECD & Food and Agriculture Organization of the United Nations, 2013; Ruy et al., 2020)	~38%/~62%
2011	~3.5	~900	(Kazimierowicz et al., 2024; OECD & Food and Agriculture Organization of the United Nations, 2013)	(OECD & Food and Agriculture Organization of the United Nations, 2013; Kazimierowicz et al., 2024)	~29%/~71%
2013	~3.8	~830	(OECD & Food and Agriculture Organization of the United Nations, 2013)	(OECD & Food and Agriculture Organization of the United Nations, 2013)	~24%/~76%
2015	~4.1	~790	(OECD & Food and Agriculture Organization of the United Nations, 2013; <i>OECD-FAO Agricultural Outlook 2023-2032</i> , 2023)	(<i>Glycerol Price Index</i> , 2025)	~20%/~80%
2017	~4.4	~810	(<i>OECD-FAO Agricultural Outlook 2023-2032</i> , 2023)	(<i>Glycerol Price Index</i> , 2025)	~16%/~84%
2019	~4.6	~880	(Ruy et al., 2020; <i>OECD-FAO Agricultural Outlook 2023-2032</i> , 2023)	(<i>Glycerol Price Index</i> , 2025; Ruy et al., 2020)	~13%/~87%
2021	~4.8	~910	(<i>OECD-FAO Agricultural Outlook 2023-2032</i> , 2023; Kazimierowicz et al., 2024)	(<i>Glycerol Price Index</i> , 2025)	~10%/~90%
2023	~5	~930	(<i>OECD-FAO Agricultural Outlook 2023-2032</i> , 2023)	(<i>Glycerol Price Index</i> , 2025)	~8%/~92%
2025	~5.2 (forecast)	~950	(<i>OECD-FAO Agricultural Outlook 2023-2032</i> , 2023; Kirici et al., 2024)	(<i>Glycerol Price Index</i> , 2025)	~6%/~94% (forecast)
2027	~5.4 (forecast)	1000 (forecast)	(<i>OECD-FAO Agricultural Outlook 2023-2032</i> , 2023)	(<i>Glycerol Price Index</i> , 2025)	~4%/~96% (forecast)

This practice not only imposes financial burdens on companies but also removes valuable metallic content from circulation, undermining principles of resource efficiency and industrial ecology. In addition, prolonged worker exposure to biocides, petroleum fractions and toxic additives has been associated with respiratory cancerogenic diseases, disorders, dermatitis, and other occupational health risks (Latinović & Marjanović, 2021).

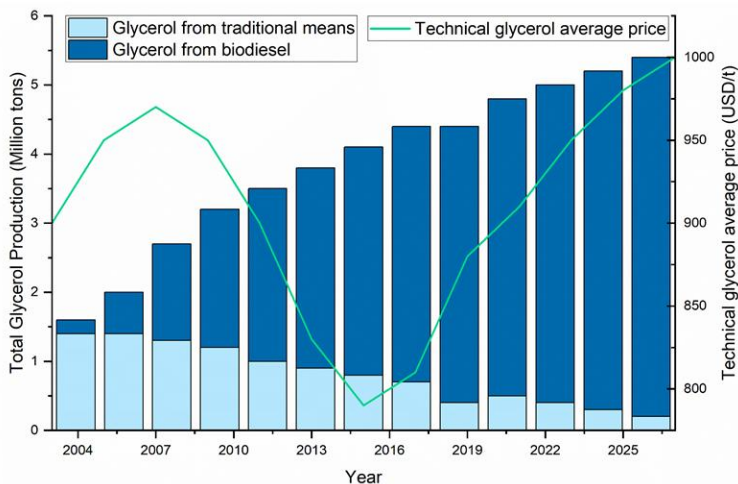


Figure 2. Global production and average annual market price of technical glycerol from 2003 to 2025 with forecasted values up to 2028 based on the data from Table 1. Figure created by the authors.

Against this backdrop, around year 2012-2013, glycerol has emerged as a candidate that addresses both sustainability challenges simultaneously (Winter et al., 2012; Wichmann et al., 2013). Its inherent properties—including high polarity, lubricity under boundary conditions, biodegradability, biostatic properties, and non-toxicity—make it an appealing substitute or supplement for mineral oils in machining applications. By eliminating biocidal contamination, glycerol-based fluids would enable metallic residues to be reclassified as non-hazardous industrial waste, facilitating their direct reintegration into recycling streams. In this sense, glycerol supports waste minimisation, resource efficiency, and industrial circularity, embodying the broader logic of the circular economy: transforming by-products from one industry into resources for another.

Nevertheless, sustainability also requires recognising trade-offs and systemic risks. One of the most critical barriers is glycerol's limited thermal stability: under elevated machining temperatures, it undergoes viscosity loss and, in extreme cases, dehydration leading to the formation of acrolein—a volatile, toxic aldehyde (Belousov, 2021; L. Huang et al., 2023). This introduces a paradox of sustainability: while one environmental burden is alleviated (hazardous waste classification), another may emerge (airborne toxic emissions). In addition, crude glycerol derived from biodiesel processes contains impurities such as methanol, soaps, and salts (Attarbach et al., 2023), which affect its physicochemical performance and raise concerns regarding economic and environmental sustainability of purification processes.

3. Methodology of the Review and Analytical Framework

The literature considered in this narrative review spans the period from approximately 2009 to 2025, reflecting the rapid growth of biodiesel production and the resulting oversupply of glycerol in recent years. Sources were identified through major academic databases (e.g., Scopus, Web of Science, ScienceDirect, Google Scholar,

EBSCO) and complemented by industry and policy reports where appropriate.

The selection of publications was guided by relevance rather than by rigid inclusion or exclusion criteria. To increase transparency and reproducibility, we applied explicit thematic inclusion criteria. Publications were retained if they met at least one of the following conditions: (1) they reported tribological, thermal-stability, or machining-performance data for neat glycerol, glycerol–water blends, or glycerol-containing formulations; (2) they examined environmental, occupational-health, or waste-management implications of MWFs relevant to comparing glycerol with conventional basestocks; (3) they provided industrial, regulatory, or economic analyses necessary for assessing feasibility or sectoral applicability. Studies were excluded if they lacked relevance to machining, lubrication, sustainability, or industrial adoption.

Rather than following a fully systematic protocol, the study draws selectively on academic and industrial sources that provide relevant insights into the potential of glycerol as a MWF within industrial contexts. The aim of this approach is not to generate an exhaustive inventory of publications, but to synthesise representative findings that illustrate the main benefits, limitations, and practical implications of glycerol adoption.

A quantitative synthesis or meta-analytic aggregation was not feasible due to the pronounced heterogeneity in experimental designs and outcome metrics across the literature. Studies differ not only in glycerol grade and purity, formulation composition, tool materials (HSS, carbide, coated systems), machining parameters, thermal loads, delivery methods (flood, MQL, dropwise), and measured outputs (COF, wear rate, torque, cutting temperature, acrolein emissions, or surface roughness), but also in the very physical systems under investigation—neat glycerol versus glycerol-water mixtures exhibit fundamentally different evaporation rates, thermal decomposition pathways, and viscosity–temperature responses. These variations yield non-commensurable effect measures that cannot be meaningfully pooled without violating statistical assumptions. For this reason, narrative synthesis remains the appropriate method for integrating the available evidence without imposing the formal restrictions of a systematic review (Basheer, 2022; Green *et al.*, 2006; Greenhalgh *et al.*, 2018; Sukhera, 2022).

The analysis proceeded by grouping findings into three thematic clusters: (1) potential advantages of glycerol, including lubrication, environmental compatibility, occupational health, and waste management benefits; (2) technical and practical limitations, particularly related to thermal stability, degradation pathways, and variability in glycerol quality; and (3) broader industrial and economic feasibility. This thematic organisation allows the review to highlight converging evidence, identify contradictory results, and point to research and policy gaps that require further attention.

4. Cluster 1 - Advantages of Glycerol in Metalworking

The potential of glycerol as a substitute or complementary component in MWFs has been highlighted as a potential feedstock for green lubricants and sustainable manufacturing practices, although the literature remains scarce (Winter *et al.*, 2012; Wichmann *et al.*, 2013; Latinović, 2021; Leiden *et al.*, 2023). Its benefits can be grouped across several interrelated dimensions: tribological performance, environmental compatibility, occupational health, waste management, and economic valorisation.

4.1 Lubrication and tribological performance

Glycerol exhibits high polarity and a capacity for hydrogen bonding, enabling the formation of stable adsorbed films on metallic surfaces (Fisher et al., 2020). These films reduce direct metal-to-metal contact during machining operations, which in turn lowers friction coefficients and wear rates (Long et al., 2019). Several studies have reported that under boundary and mixed lubrication conditions, glycerol demonstrates comparable or even superior lubricating properties relative to conventional mineral oils (Chen et al., 2013; Long et al., 2019; Tamayo et al., 2022; Momeni et al., 2024). Its viscosity at ambient temperature is advantageous for forming consistent lubrication layers, and its miscibility with water provides flexibility in tailoring formulations to specific machining environments (Shi et al., 2014; Momeni et al., 2024).

4.2 Biodegradability and environmental compatibility

A major advantage of glycerol is its non-toxic (Regulation - 1272/2008 - EN - Clp Regulation - EUR-Lex, n.d.), biodegradable nature. Unlike mineral oils that persist in ecosystems and accumulate in soil or water bodies (Nowak et al., 2019), glycerol rapidly degrades under aerobic and anaerobic conditions (Takamura et al., 2012; Ríos et al., 2024). This property aligns with regulatory pressures and corporate commitments to reduce environmental burdens from industrial operations. By integrating glycerol-based MWFs, companies can reduce the environmental footprint of manufacturing activities and contribute to broader sustainability goals, particularly within circular economy frameworks.

4.3 Occupational health improvements

Conventional MWFs typically contain additives such as formaldehyde-releasing biocides and petroleum fractions that pose significant risks to workers (Latinović & Marjanović, 2021). Prolonged exposure has been linked to dermatitis, asthma, and other occupational diseases (Latinović & Marjanović, 2021). Glycerol, by contrast, is recognised as safe for dermal and inhalation exposure within common industrial concentrations, having long been used in food, cosmetic, and pharmaceutical industries (Becker et al., 2019; Akinsulie et al., 2025). Its substitution in MWF formulations therefore represents a potential pathway to improving occupational health and safety conditions across industrial workshops.

4.4 Waste management benefits

A key dimension of sustainability in the use of metalworking fluids (MWFs) is the impact they exert on downstream waste management, particularly concerning the classification of metallic residues. Under conventional practice, metal chips and swarf contaminated with emulsions containing petroleum fractions and biocidal additives are categorised as hazardous waste streams. This classification is mandated by European Union regulations, as well as national hazardous waste frameworks, which define such residues as requiring specialised handling, transportation, and treatment (Directive - 2008/98 - EN - Waste Framework Directive - EUR-Lex, n.d.; European Court of Auditors, 2023). The presence of toxic substances—formaldehyde-releasing agents,

chlorinated compounds, and persistent petroleum fractions—renders metallic residues unsuitable for direct recycling, thereby forcing manufacturers to rely on specialised landfill disposal or other high-cost disposal methods (Kumar *et al.*, 2023; Rietdorf *et al.*, 2024).

The implication of this classification extends beyond mere administrative labelling. Once chips enter the hazardous waste stream, they must be collected in segregated containers, stored under restrictive conditions, and transferred only by licensed contractors. Furthermore, the contaminated material cannot be directed to secondary metallurgical processes without prior decontamination, which is often technically impractical (Kumar *et al.*, 2023). As a result, valuable metallic content is effectively removed from circulation, undermining efforts toward industrial resource efficiency and circular economy. By contrast, glycerol-based MWFs alter this waste trajectory at its origin (Figure 3).

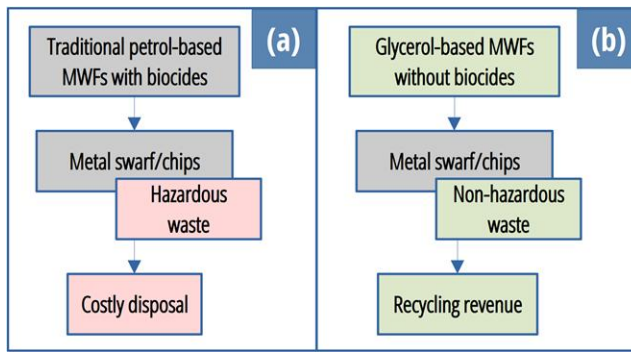


Figure 3. Comparison of waste-flow pathways for metallic swarf under traditional petroleum-based (a) versus glycerol-based metalworking fluids (b). Figure created by the authors.

In the absence of toxic additives and biocidal contaminants, metallic swarf generated during machining can be classified as non-hazardous industrial waste. This classification shift carries significant environmental implications: residues can be integrated directly into established recycling pathways without the need for costly decontamination or controlled destruction. From a regulatory perspective, the adoption of biodegradable and non-toxic fluids aligns with EU directives encouraging waste minimisation and resource valorisation, particularly under the Waste Framework Directive and the Circular Economy Action Plan. The transition from hazardous to non-hazardous categorisation thus represents more than a semantic distinction. It fundamentally repositions metallic residues within the industrial metabolism: from a waste stream requiring isolation and destruction to a recyclable resource compatible with circular production systems. In doing so, glycerol enables manufacturers to meet environmental compliance obligations while simultaneously contributing to broader policy objectives of waste reduction, resource efficiency, and sustainable manufacturing.

4.5 Economic opportunities

The persistent oversupply of crude glycerol resulting from biodiesel production has depressed its market price, creating an incentive to identify new industrial applications that can absorb surplus volumes. Utilising glycerol as a base component in MWFs represents a valorisation strategy that connects two industries: renewable energy and

manufacturing. By diverting low-cost, abundant glycerol streams into metalworking applications, companies could simultaneously reduce dependence on petroleum-derived lubricants and contribute to stabilising glycerol markets. Such industrial symbiosis strengthens the economic argument for integrating glycerol into machining operations and enhances the sustainability profile of both sectors.

5. Cluster 2 - Technical and practical limitations

While glycerol offers several advantages as a potential base for MWFs, the literature also highlights substantial limitations that restrict its immediate and universal applicability in industrial contexts. These limitations primarily arise from thermal behaviour, chemical stability, quality variability, and compatibility with existing manufacturing systems.

5.1 Thermal stability issues

A critical drawback of neat glycerol as a MWFs base stock is its limited thermal stability. Machining operations frequently involve elevated temperatures at the tool–workpiece interface, sometimes exceeding 200–300 °C (dos Santos et al., 2025). Under such conditions, glycerol’s viscosity decreases significantly, leading to reduced lubricity and insufficient cooling performance (S. Huang et al., 2024). This undermines one of the key functions of MWFs: heat dissipation and lubrication. The resulting thermal thinning can accelerate tool wear and compromise surface finish quality, particularly in high-speed or heavy-duty machining.

At high temperatures, glycerol can undergo dehydration reactions that yield acrolein, a volatile and highly irritating aldehyde (Condotta et al., 2025; J. Liu et al., 2025). Acrolein is recognised as toxic to both humans and the environment, with acute exposure leading to respiratory irritation, eye damage, and systemic toxicity (Stevens & Maier, 2008). The potential formation of acrolein during machining raises concerns about worker safety and environmental emissions, partially offsetting glycerol’s advantages in occupational health and sustainability. This issue is especially relevant when machining alloys that generate localised high temperatures at the cutting zone. Beyond acrolein formation, glycerol is susceptible to other thermally induced degradation pathways, producing polymers, carbonaceous residues, or volatile by-products (Almazrouei et al., 2022; Batista et al., 2022; Zhang et al., 2021). These processes alter the physical and chemical characteristics of the fluid, resulting in inconsistent performance over time. Degradation also complicates fluid maintenance and shortens service life, raising questions about operational cost-effectiveness relative to conventional mineral oils or synthetic alternatives.

Thermal degradation of glycerol under machining-relevant conditions has been extensively characterised by thermogravimetric and oxidative studies. Glycerol was found to exhibit strong temperature–viscosity sensitivity, with measurable viscosity reduction and thinning of lubricating films observed above ~100 °C in tribological contacts—even without chemical breakdown (Björling & Shi, 2019; Ferreira et al., 2017). However, under oxidative conditions (e.g., air atmosphere), mild degradation pathways can initiate at significantly lower temperatures than previously assumed. Recent evidence shows that slow oxidative decomposition may begin between ~133–175 °C in the presence of oxygen,

particularly under long exposure times, with low-molecular-weight products such as formic, acrylic, and acetaldehyde acids detected (Jaegers *et al.*, 2021). This early onset of degradation, though kinetically limited, becomes increasingly significant as temperatures rise. Thermogravimetric analyses confirm that glycerol remains thermally stable up to ~ 150 °C under typical ramp rates (Castelló *et al.*, 2009), with major mass loss initiating between 180–200 °C. The most rapid decomposition occurs between ~ 200 –250 °C, peaking around 230–246 °C, and completing by 270 °C, depending on heating rate and atmosphere (Almazrouei *et al.*, 2022; Castelló *et al.*, 2009; Fischer, n.d.). These transformations primarily involve volatilisation and oxidation, rather than solid decomposition. In inert atmospheres, degradation is delayed, with onset near 199 °C and evaporation dominating below ~ 300 °C (Castelló *et al.*, 2009; Fischer, n.d.). The quantified thermal degradation curve summarising remaining mass vs. temperature is shown in Figure 4.

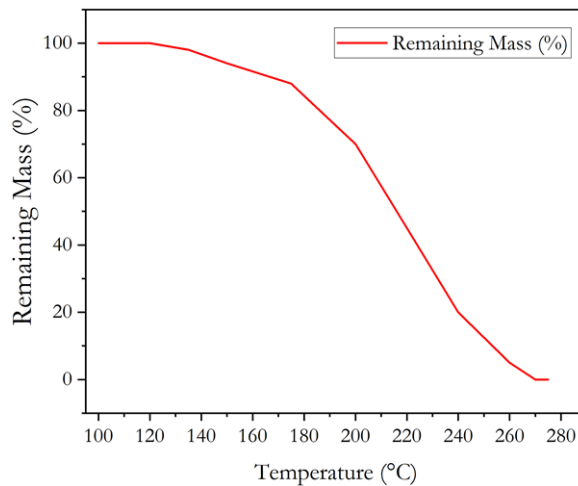


Figure 4. Thermogravimetric profile of glycerol showing remaining mass (%) as a function of temperature in air between 100–280 °C, compiled from secondary TGA data (Almazrouei *et al.*, 2022; Castelló *et al.*, 2009; Jaegers *et al.*, 2021). Figure created by the authors.

Above ~ 230 °C, more aggressive pathways dominate—including C–C and C–O bond cleavage—yielding volatile aldehydes, ketones, and carbonaceous residues. In low-moisture air, surface-catalysed dehydration to acrolein and polymeric byproducts becomes prominent (J. Liu *et al.*, 2025; L. Liu *et al.*, 2023; Zhang *et al.*, 2021). A conceptual classification of the main degradation stages across increasing temperatures is provided in Figure 5, helping visualise the progressive breakdown and loss of functional fluidity across machining-relevant conditions.

These degradation regimes are especially relevant in high-speed machining where flash temperatures can exceed 250 °C within milliseconds. For example, dry milling of magnesium alloys has produced chip-zone temperatures of ~ 322 °C (Kuczmazewski *et al.*, 2022), while machining of nickel-based alloys can exceed 400 °C (Pérez-Salinas *et al.*, 2024). In such cases, neat glycerol is rapidly pushed beyond its thermal stability limits, resulting in both loss of lubricity and generation of harmful byproducts.

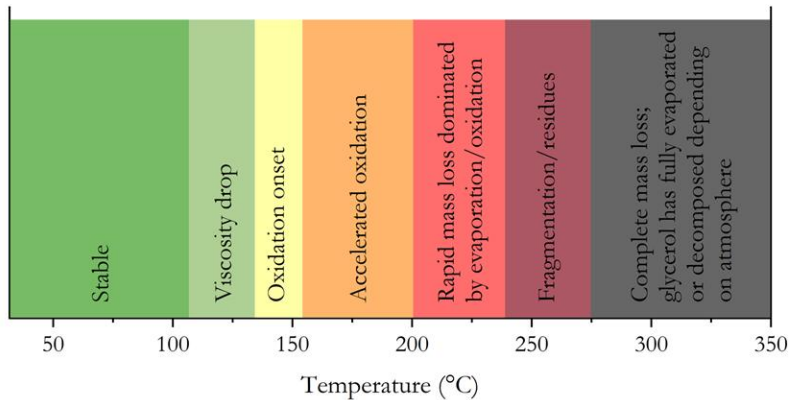


Figure 5. Indicative thermal-response domains of glycerol under increasing temperature, illustrating the approximate transition from stable physicochemical behaviour to full decomposition. Based on synthesis of published thermal and tribological data (Almazrouei et al., 2022; Björling & Shi, 2019; Castelló et al., 2009; Fischer, n.d.; Jaegers et al., 2021; J. Liu et al., 2025; L. Liu et al., 2023; Zhang et al., 2021). Figure created by the authors.

These thermal thresholds and regimes refer primarily to neat glycerol. In aqueous glycerol–water systems, evaporation and degradation behaviour differ in two important respects. First, aerosol and droplet studies show that dilution in water depresses the effective vapour pressure of glycerol and slows its evaporation: measurements of the hydrogen-bond network in aqueous glycerol aerosols, kinetic studies of glycerol–water particles, and sessile droplet evaporation experiments consistently report that water-rich mixtures retain glycerol for longer times and lose mass predominantly as water at moderate temperatures (Thayyil Raju et al., 2022; Weeraratna et al., 2021; Wright et al., 2016). Second, thermogravimetric analyses of bulk mixtures demonstrate that glycerol–water blends remain glycerol-stable during the initial mass-loss step, with water removal dominating up to roughly 140–160 °C and no detectable decomposition of the organic phase even at water contents up to about 30 wt% (Castelló et al., 2009; Gonçalves et al., 2022). Collectively, these results imply that, under comparable external thermal loads, glycerol–water blends exhibit slower glycerol volatilisation and an effectively delayed onset of oxidative degradation relative to neat glycerol, although the absolute temperature limits remain strongly conditioned by composition, exposure time, and atmosphere.

From this, a more refined operational envelope for neat glycerol can be proposed. Glycerol remains chemically and tribologically stable below ~130–150 °C, a range typical for low-speed operations such as HSS drilling, tapping, reaming, and aluminium finishing. Between ~150–200 °C, partial oxidative degradation may occur, and lubrication regimes require precise thermal control via feed regulation, fluid dilution, or minimal quantity lubrication systems. Beyond ~210 °C, formation of reactive species such as acrolein becomes likely, rendering neat glycerol unsuitable without stabilising additives. In regimes where tool–chip interface temperatures exceed ~250 °C—common in carbide roughing, aggressive slotting, or superalloy machining—glycerol undergoes irreversible breakdown and must be substituted or fortified with hybrid basestocks, antioxidant packages, or engineered cooling strategies. The applicable envelope for glycerol–water blends is shifted

upward to the extent described above, owing to their delayed glycerol volatilisation and decomposition behaviour. These thermochemical thresholds underscore the need for temperature-tailored formulations in bio-lubrication and motivate future work in real-time thermal monitoring and predictive modelling to extend fluid lifetime under high-performance conditions.

5.2 Compatibility with industrial infrastructure

Metalworking facilities are typically optimised for petroleum-based MWFs, with machine designs, pumps, filters, and maintenance protocols calibrated to conventional fluids (S. Huang *et al.*, 2024). Glycerol's high viscosity at lower temperatures and its hygroscopic nature (tendency to absorb water) may cause technical incompatibilities with current systems. Furthermore, modifications to storage, handling, and fluid recycling processes may be necessary, creating additional investment barriers for industrial adoption. Moreover, the quality of glycerol available for industrial use is highly variable. Crude glycerol derived from biodiesel processes often contains impurities such as methanol, soaps, salts, and unreacted fats (Attarbach *et al.*, 2023). These contaminants can drastically affect lubricity, viscosity, and thermal behaviour, as well as potentially corrode machine components (Abdul Raman *et al.*, 2019; Attarbach *et al.*, 2023). While pharmaceutical-grade glycerol exhibits greater stability and consistency, its higher cost undermines the economic rationale for large-scale industrial application. This quality gap presents a major challenge to deploying glycerol as an industrial MWF without extensive purification, which itself adds costs and energy burdens.

6. Cluster 3 – Industrial and economic feasibility

The juxtaposition of benefits and limitations reveals a complex picture of glycerol's potential role in the industrial metalworking sector. On the one hand, glycerol offers substantial sustainability gains: it is abundant, non-toxic under standard conditions, and capable of transforming hazardous waste streams into recyclable ones. On the other hand, unresolved technical issues, particularly regarding thermal behaviour and chemical degradation, limit its immediate large-scale adoption. This section synthesises the existing evidence, highlights contradictions, and evaluates the broader industrial feasibility within a circular economy framework.

The literature demonstrates considerable heterogeneity in reported tribological performance of glycerol. While some studies highlight significant reductions in friction and wear under boundary lubrication conditions, others observe unstable results at elevated machining speeds. This inconsistency may partly arise from differences in glycerol purity and formulation. Crude glycerol, for instance, may enhance lubricity due to the presence of fatty acid residues, but these same impurities can also trigger corrosion or thermal instability. Conversely, purified pharmaceutical-grade glycerol offers stability and reproducibility, yet its cost undermines the economic argument for widespread industrial adoption. These unresolved contradictions highlight the necessity of standardised testing protocols and comparative studies across different grades of glycerol.

From a sustainability perspective, glycerol's biodegradability, safety profile, and potential to reduce hazardous waste classification of metal chips provide compelling

advantages. However, these benefits are counterweighted by risks associated with thermal degradation and acrolein formation. The irony is that the very property which strengthens glycerol's environmental credentials—its chemical reactivity—becomes a liability in high-temperature machining contexts. This duality underscores the importance of considering not only laboratory-scale tribological results, but also the full operational lifecycle of fluids in industrial practice.

6.1 Industrial feasibility in circular economy frameworks

From the perspective of industrial feasibility, glycerol's valorisation as a MWF embodies the essence of circular economy: it enables a waste stream from one sector—the biodiesel industry—to become a productive input in another, namely metalworking. Yet the translation of this principle into practice requires more than theoretical alignment. It must withstand scrutiny in terms of technical reliability, regulatory compliance, and financial incentives.

On the regulatory side, the adoption of glycerol as a non-toxic and biodegradable machining fluid offers a clear pathway to reduce the classification of machining residues as hazardous waste. This reclassification is not only environmentally aligned but also creates a direct economic incentive for firms by lowering disposal costs and enabling revenue recovery through scrap sales.

Economic considerations further reinforce the industrial logic. The management of metallic swarf in Europe typically incurs disposal costs in the range of €100–700 per tonne when residues are classified as hazardous waste, depending on local regulations and treatment options (“Hazardous Waste Companies in UK,” n.d.; “Hazardous Waste Disposal Price List | Opasnite.Bg,” n.d.). In contrast, clean recyclable swarf can fetch €150–300 per tonne on the secondary metals market (Ploumis, n.d.; *Scrap Metal Price Index - Germany - Metaloop*, n.d.). With possible difference of 1000€/tonne, regarding an estimated 2.5–3 million tonnes generated annually at the European level, and globally, where machining residues exceed 20 million tonnes per year, (Pauliuk et al., 2013; Lopez et al., 2022; “World Steel in Figures 2022,” n.d.), this cost differential translates into a swing of several hundred million euros across the sector.

However, industrial feasibility is not solely a matter of economics. To be a credible substitute, glycerol must also meet performance thresholds that ensure process reliability. In its current state, this restricts adoption to operations where thermal loads remain manageable. Still, when the economic benefit of simplified waste management is combined with targeted technical applicability, the business case strengthens considerably. For many firms, the capacity to transform machining residues from a costly liability into a source of revenue will outweigh the limitations that prevent universal deployment.

While glycerol cannot displace petroleum-based fluids across all machining operations, its selective adoption in defined application ranges offers a compelling blend of environmental responsibility and financial return. For individual firms, particularly in automotive, aerospace, and heavy machinery industries where machining volumes are highest, such gains can directly influence competitiveness and profitability. The alignment of regulatory, economic, and sustainability imperatives suggests that glycerol-based MWFs represent not just a technical experiment but a strategic opportunity for industry within the framework of circular economy. Ultimately, the feasibility of glycerol in industrial

practice rests on this dual foundation: technical sufficiency in defined machining windows, and economic superiority in waste management. Within a circular economy framework, these two dimensions converge. By enabling the revalorisation of metallic residues, glycerol shifts the role of MWFs from a hidden cost driver to a facilitator of both sustainability and financial return, providing a compelling rationale for selective adoption in modern manufacturing systems.

6.2 Defining the Application Range

The synthesis of benefits and limitations allows for a more precise delineation of the conditions under which glycerol can realistically be integrated into the industrial metalworking sector. Rather than viewing glycerol as a universal replacement for petroleum-based MWFs, its potential lies in carefully defined application windows that balance technical feasibility, economic logic, and sustainability imperatives.

6.2.1 Conditions where glycerol is feasible (low-moderate T, specific alloys)

Glycerol is most defensible where the cutting zone remains in a low-to-moderate thermal regime and where boundary lubrication dominates over bulk cooling. In such windows its polarity and film-forming tendency reduce friction and wear without provoking rapid thermal thinning or degradation (Tamayo *et al.*, 2022; Trajkovski *et al.*, 2023; Ganesh *et al.*, 2023; Okhiria *et al.*, 2024).

Furthermore, the selection of tool material is of considerable importance in machining processes. High-speed steel (HSS), which is frequently employed in metal turning and milling, experiences a more pronounced loss of hot hardness at elevated temperatures compared to cemented carbides (Ghuge & Palande, 2024). As a result, HSS tools benefit to a greater extent from the use of cutting fluids that minimise friction and improve heat dissipation, particularly at moderate cutting speeds and feeds (*ref.*). In contrast, tungsten-carbide (TCT) inserts—including standard ISO geometries such as MGM—are engineered to withstand higher operational temperatures and are commonly applied under dry conditions or minimum-quantity lubrication (MQL) (Bhowmik *et al.*, 2025). However, it is noteworthy that dry machining is not universally optimal for all carbide applications. Specifically, when finishing quality, susceptibility to adhesive wear, or occurrence of built-up edge (BUE) are limiting factors, the application of polar, film-forming fluids may provide beneficial effects even in carbide-based operations at moderate speeds (Gupta *et al.*, 2023; Duan *et al.*, 2025).

With respect to the temperature envelope identified in previous findings, and considering operational and material-specific constraints, the following guidance can be formulated: For HSS tools engaged in low-to-medium speed turning, drilling, reaming, and tapping of mild steels and various aluminium or copper alloys, the use of glycerol—either neat or as an aqueous blend—has been shown to reduce friction and tool wear, enhance surface finish, and simplify chip waste classification (Momeni *et al.*, 2024).

In carbide finishing, reaming, or low-to-medium speed drilling of mild steels and free-machining alloys, the strategic application of a thin glycerol film may suppress adhesive wear mechanisms and minimise BUE in aluminium and brasses. Modest water dilution in such blends aids in controlling viscosity and enhancing heat removal (Gupta *et al.*, 2023). By contrast, for high-speed, high-load rough machining with carbide tools—

particularly on hard-to-cut alloys such as austenitic stainless steels or nickel-based superalloys—the local generation of flash temperatures and prolonged tool-chip contact promotes thermal thinning and dehydration of glycerol; in these conditions, the risks can outweigh potential tribological improvements (Shokrani et al., 2024). For aluminium alloys prone to BUE when machined with carbide tools, glycerol may offer advantages at moderate cutting speeds due to its polarity, which can disrupt adhesive interactions at the tool–chip interface; however, attention should be paid to using diluted fluids and controlling application to avoid local thermal accumulation. During tapping and thread forming in steels with HSS tools, moderate speeds combined with glycerol-containing fluids can lead to reduced torque and improved surface integrity through enhanced boundary lubrication (Demmerling, 2023).

From a delivery and formulation perspective, a preference should be given to sustained application (e.g., light flooding or carefully controlled MQL), conservative chip loads, and the use of glycerol–water blends to optimise viscosity and convective cooling while preventing local overheating. For carbide machining, glycerol should primarily be considered an auxiliary agent for finishing and anti-adhesion purposes in temperature-managed environments rather than a universal substitute for dry or conventional high-pressure coolant strategies in demanding, high-speed operations. Moreover, exhaust and aerosol emissions should be carefully managed during atomisation, with process temperatures kept well below degradation thresholds.

6.2.2 Conditions where limitations prevail (high-speed machining, thermal load)

Under conditions of high cutting speeds and elevated tool loads, characteristic of process regimes such as high-feed carbide roughing, heavy slotting and milling, or the machining of difficult-to-cut superalloys (austenitic and duplex stainless steels, Ni/Co-based alloys, hardened steels), the limitations of glycerol as a metalworking fluid become dominant. Key issues include rapid viscosity reduction due to thermal thinning, insufficient bulk cooling capacity, and frequent rupture of the lubricating film, all of which intensify adhesive and diffusion wear. Moreover, elevated flash temperatures promote dehydration reactions that can lead to acrolein formation, undermining the occupational health rationale for glycerol and necessitating additional ventilation measures. Repeated thermal cycling accelerates chemical transformations and fouling, shortening service life and complicating system maintenance. At the same time, high ambient viscosity, hygroscopicity, and the particulate load from degradation residues impose additional stresses on pumps and filters designed for conventional fluids. In such environments, its adoption is imprudent unless fundamental formulation modifications and comprehensive process re-engineering are undertaken.

6.2.3 Sectoral feasibility and implementation context

Sectoral comparison is warranted because the feasibility of glycerol is bounded by the thermal envelope, tooling–material combinations, infrastructure, and regulatory context, all of which differ markedly across industries. The review identifies defensible use at low-to-moderate temperatures (especially HSS and selected carbide finishing) and sharp limitations at high-speed/high-heat regimes; waste and economic effects also scale with swarf volumes and hazardous-waste classification. A concise cross-industry snapshot

therefore operationalises the “application window” and clarifies where standards and monitoring would most accelerate uptake.

Accordingly, we contrast four settings—small/medium workshops; automotive; heavy machinery/shipbuilding; aerospace—with distinct machining intensity and governance requirements (Table 2).

Table 2: Sectoral feasibility and implementation context of glycerol-based MWFs. Comparative assessment across small/medium workshops, automotive, heavy machinery/shipbuilding, and aerospace.

Sector	Feasible adoption window	Formulation & delivery	Infrastructure / standards	Key risks	Near-term feasibility	Evidence anchors (this review)
Small/ medium workshops	Mixed jobs with frequent HSS use on mild steels and common Al/Cu alloys at modest cutting speeds; broad window wherever thermal loads remain low–moderate and tolerances are typical of general engineering workshops (Candane et al., 2013).	Neat or diluted glycerol; light flood or cautious MQL; viscosity and concentration must be monitored due to hygroscopicity.	Simple inline viscosity/conductivity checks; no major re-engineering of coolant systems required (Kwon & Pallerla, 2000)	Moisture uptake; variable crude-glycerol quality; handling of viscous fluids.	High for selected operations at low thermal load.	HSS benefit; viscosity/hygroscopicity & infrastructure constraints.
Automotive	Low–moderate-T lines; HSS tapping/reaming; Finishing and semi-finishing lines on alloy steels and Al cast/wrought alloys under controlled thermal loads (Krajnik et al., 2021; Leiden et al., 2023; Santos et al., 2016)	Glycerol–water blends; metered flood or MQL; temperature must remain below decomposition limits.	Baseline crude-glycerol quality threshold; inline viscosity/conductivity/TOC; ventilation and aerosol control.	Thermal thinning; local acrolein formation at hotspots; dimensional-cleanliness constraints.	Moderate in governed finishing/semi-finishing lines.	Adoption window; emissions/acrolein; waste & economics.
Heavy machinery / shipbuilding	Low–moderate-T rough- to semi-finish of large steel & cast irons components; long cycles, modest speeds (de Sousa et al., 2018; Uriarte et al., 2013)	Diluted glycerol blends to manage viscosity; steady light-flood; chip evacuation priority.	Bulk-fluid handling and moisture control; robust filtration and swarf-recycling logistics.	Degradation if local heat increases; acrolein hotspots; viscosity-driven pumping issues.	Moderate–High where long-cycle, modest-speed cells already exist.	Waste-flow & recycling logic; viscosity/infrastructure implications.
Aerospace	Narrow: non-critical Al finishing; selected drilling/reaming at conservative speeds (Jemielniak, 2021; Ulutan & Ozel, 2011)	Stabilised/hybrid glycerol formulations; tight thermal control; qualified MQL/flood only.	Strict qualification and emission compliance; filtration compatibility; OEM documentation requirements.	Film rupture at high heat; surface-integrity risk; certification exposure.	Low near-term, contingent on proof of thermal stability & qualification.	High-speed/high-heat limits; degradation & emissions; qualification constraints.

Small/medium workshops offer the broadest near-term window given moderate speeds, HSS-dominant operations, and simpler infrastructure changes (Candane et al., 2013; Yawara & Intanon, 2019); automotive supports selective deployment on

finishing/semi-finishing lines where temperatures are controlled (Leiden et al., 2023); heavy machinery/shipbuilding involves large parts, long cycles, modest cutting speeds, and very high swarf volumes, amplifying waste-management and economic stakes (Deja et al., 2017; Guo, 2023); aerospace remains the narrowest window owing to higher thermal loads, stringent surface-integrity requirements, and emission controls (Klocke et al., 2011; Thakur & Gangopadhyay, 2016; Ulutan & Ozel, 2011).

Taken together, the sectoral comparison (Table 2) reveals a gradient in near-term feasibility—small/medium workshops → automotive → heavy machinery/shipbuilding → aerospace—driven by four determinants: thermal envelope, tooling/material pairing, infrastructure sensitivity, and waste/economic leverage. Small and medium workshops present the broadest window because feasible use is concentrated in low-to-moderate temperature operations, frequently with HSS tools, where glycerol's boundary-lubrication benefits can be realised without breaching degradation thresholds (Winter et al., 2012; Wichmann et al., 2013; Tamayo et al., 2022). Automotive lines support selective adoption on governed finishing and semi-finishing operations, while heavy machinery and shipbuilding offer attractive waste-management and scrap-logistics gains in cells where cutting speeds and local temperatures remain moderate. Aerospace exhibits the narrowest window, largely confined to non-critical aluminium finishing and carefully controlled drilling/reaming, because higher thermal loads, stringent surface-integrity requirements, and emission constraints tighten the operating space.

6.2.4 Harmonisation feasibility (standards and infrastructure)

Cross-industry harmonisation is feasible if framed as performance-class standards rather than a single, prescriptive formulation. First, glycerol-based MWFs can be nested under the existing ISO lubricant taxonomy (class L, family M—metalworking) as a defined sub-class with baseline composition descriptors (water content, conductivity, viscosity band, impurity ranges) following the ISO 6743 framework (*ISO 6743-7*, n.d.), and aligned with the EU Ecolabel Lubricants scheme, which assigns metalworking fluids to the Accidental Loss Lubricants (ALL) product group and explicitly cross-references ISO 6743 families in scope definitions (*Consolidated TEXT*, n.d.). This provides a common language across sectors while allowing sector-specific annexes. Second, a minimum comparative test suite can be standardised using widely adopted methods: anti-wear screening by Four-Ball (ASTM D4172), and hole-making performance by Tapping-Torque (ASTM D5619/D8288), which are already used to benchmark MWFs and correlate with shop-floor behaviour (D02 Committee, n.d.). Third, emissions control can be harmonised via compliance with established occupational-exposure limits for acrolein (e.g., OSHA/NIOSH 0.1 ppm TWA; EU IOELV-based regimes), implemented as pass/fail criteria for ventilation/monitoring during MQL or light-flood application (*ACROLEIN | Occupational Safety and Health Administration*, n.d.). Fourth, delivery and infrastructure can be aligned on minimum monitoring (inline viscosity, conductivity, TOC) and moisture-management requirements; for MQL specifically, current guidance acknowledges the absence of a formal international definition, so harmonised practice should adopt a conservative usage band until an ISO/DIN profile is established (Walker, 2015). These elements directly target the common constraints identified in this review—thermal envelope and degradation risk, viscosity/hygroscopic sensitivity, and sector-agnostic

waste/economic drivers—supporting a realistic pathway to cross-industry uptake under a unified, performance-based umbrella.

6.2.5 Possible strategies to expand applicability (stabilisers, hybrid formulations)

The expansion of glycerol's applicability as a MWF requires a coordinated approach that integrates advances in chemistry, process control, and system infrastructure. On the chemical side, the introduction of thermal stabilisers and antioxidants can delay dehydration and suppress acrolein formation (Kächele *et al.*, 2014; Verma & Yadav, 2024), while pH buffering mitigates acid-catalysed degradation pathways (L. Huang *et al.*, 2023). Water–glycerol blends may be employed to adjust viscosity and improve convective cooling, with careful balancing of humectant properties to limit hygroscopic effects. Boundary-film enhancers such as polar additives, esters, or phosphates can sustain low-friction conditions at reduced dosages (Yi *et al.*, 2024), whereas hybrid biobased basestocks—including partial esters and polyols—have the potential to elevate the thermal ceiling without compromising biodegradability (Raof *et al.*, 2022).

In parallel, particle-assisted tribology through selected nano-additives could enhance load-carrying capacity (Mishra & Aggarwal, 2023), provided toxicological and waste-management constraints are addressed. From a process perspective, the effective use of glycerol necessitates maintaining cutting speeds and feeds within a controlled thermal envelope, favouring finishing operations and moderate-load drilling or reaming. Delivery optimisation should emphasise light flood or metered minimum-quantity lubrication targeted at the tool–chip interface, while avoiding aerosolisation at elevated temperatures. Additional thermal management could be achieved through sharper tools, honed-edge geometries, intermittent dwell reduction, and the use of chip breakers that reduce contact time and thereby limit frictional heating. Thermochemical modelling studies of glycerol dehydration indicate that reaction rates are strongly temperature-dependent and can be shifted by modifying local pH, water activity, and catalytic surfaces.

These insights suggest practical stabilisation strategies: maintaining higher water activity in blends to suppress dehydration kinetics, incorporating buffering agents to slow acid-catalysed breakdown, or employing additives that promote endothermic hydrogen-bond restructuring. Such measures do not eliminate degradation at high temperatures but can shift the onset of acrolein formation upward by ~20–40 °C under controlled conditions, widening the usable window for finishing operations and temperature-managed carbide machining.

On the infrastructural level, reliable deployment requires upgrading pumps and filtration systems to accommodate higher viscosity and particulate loads, coupled with moisture control in storage and recirculation loops. Inline monitoring of viscosity, conductivity, and total organic carbon is essential to detect early degradation and schedule timely fluid refreshment. A sourcing strategy based on standardised specifications for crude glycerol or cost-effective purification can further reduce batch variability. Taken together, these measures define a conditional decision framework: glycerol is best applied with high-speed steel at modest speeds or carbide tools in temperature-managed finishing, while its use in high-heat carbide roughing remains inadvisable unless stabilised or hybrid formulations demonstrably control degradation and emissions. Ultimately, only where the environmental and occupational-health advantages are preserved—after accounting for

stabiliser toxicology and ventilation demands—can glycerol be justified as a sustainable option. With targeted stabilisers, hybrid basestocks, and disciplined process management, its feasible window can be widened incrementally, but without such measures glycerol remains most suitable as a selective, sustainability-oriented alternative for low-to-moderate thermal regimes rather than a wholesale substitute for conventional fluids in high-energy machining.

7. Conclusion

This review has critically assessed the potential of glycerol as a sustainable alternative to conventional MWFs, highlighting both its enabling properties and its constraints. Glycerol's appeal lies in its dual status as an oversupplied by-product of biodiesel production and as a non-toxic, biodegradable compound with strong boundary-lubrication behaviour. Evidence indicates that its industrial relevance is niche but material: low-to-moderate temperature machining with HSS, drilling, tapping and reaming of mild steels, and selected carbide finishing of aluminium and brass in small/medium workshops, automotive finishing lines, and specific heavy-machinery/shipbuilding cells where thermal loads are governed and waste-management gains are substantial. Under these conditions, glycerol-based fluids can enable reclassification of swarf from hazardous to recyclable waste and support circular-economy objectives. At the same time, neat glycerol remains clearly limited by thermal instability, acrolein formation and degradation at elevated cutting temperatures. Glycerol–water mixtures show slower glycerol volatilisation and a modestly extended thermal window, but their safe operating range remains strongly composition- and temperature-dependent and does not remove the fundamental need for careful thermal control.

Future research should prioritise the development of hybrid glycerol-based formulations that incorporate stabilisers, esters, or functional nanoparticles to increase thermal robustness and maintain lubricity under higher interface temperatures. Advances in thermochemical stabilisation could shift the onset of glycerol dehydration and acrolein formation, widening applicability beyond the current low- to moderate-temperature envelope. Parallel efforts are needed to establish standardised industrial protocols for crude-glycerol purification, impurity quantification, and in-process monitoring, as variability in feedstock quality remains a barrier to predictable shop-floor behaviour. Harmonised emission-monitoring procedures, especially for acrolein under MQL and light-flood conditions, would further enhance operational safety. Finally, experimental life-cycle assessments integrating energy use, emissions, waste-stream reclassification, and end-of-life impacts are essential for converting theoretical sustainability benefits into measurable industrial baselines and policy-relevant evidence.

Overall, glycerol should be regarded not as a universal replacement for petroleum-based MWFs but as a selective, sustainability-oriented option whose justification depends on respecting its thermal limits, exploiting clearly defined industrial niches, and, where appropriate, leveraging glycerol–water blends. These conclusions rest on a heterogeneous and methodologically diverse evidence base; accordingly, the review delineates application windows rather than proposing universally generalisable performance metrics, consistent with the role of narrative syntheses in emerging technical domains.

References

- Abdul Raman, A. A., Tan, H. W., & Buthiyappan, A. (2019). Two-Step Purification of Glycerol as a Value Added by Product From the Biodiesel Production Process. *Frontiers in Chemistry*, 7. <https://doi.org/10.3389/fchem.2019.00774>
- ACROLEIN | *Occupational Safety and Health Administration*. (n.d.). Retrieved November 10, 2025, from https://www.osha.gov/chemicaldata/51?utm_source=chatgpt.com
- Akinsulie, A., Raj, P. S., Bergfeld, W. F., Belsito, D. V., Cohen, D. E., Klaassen, C. D., Liebler, D. C., Marks Jr, J. G., Peterson, L. A., Shank, R. C., Slaga, T. J., Snyder, P. W., Fiume, M. M., & Heldreth, B. (2025). Safety Assessment of Glycerin Ethoxylates as Used in Cosmetics. *International Journal of Toxicology*, 44(2_suppl), 75S-91S. <https://doi.org/10.1177/10915818251342558>
- Almazrouei, M., Adeyemi, I., & Janajreh, I. (2022). Thermogravimetric assessment of the thermal degradation during combustion of crude and pure glycerol. *Biomass Conversion and Biorefinery*, 12(10), 4403–4417. <https://doi.org/10.1007/s13399-022-02526-w>
- Attarbach, T., Kingsley, M. D., & Spallina, V. (2023). New trends on crude glycerol purification: A review. *Fuel*, 340, 127485. <https://doi.org/10.1016/j.fuel.2023.127485>
- Basheer, A. (2022). The Art and Science of Writing Narrative Reviews. *International Journal of Advanced Medical and Health Research*, 9(2), 124. https://doi.org/10.4103/ijamr.ijamr_234_22
- Batista, M., Carvalho, S., Carvalho, R., Pinto, M. L., & Pires, J. (2022). Waste-Glycerol as a Precursor for Carbon Materials: An Overview. *Compounds*, 2(3), 222–236. <https://doi.org/10.3390/compounds2030018>
- Becker, L. C., Bergfeld, W. F., Belsito, D. V., Hill, R. A., Klaassen, C. D., Liebler, D. C., Marks Jr, J. G., Shank, R. C., Slaga, T. J., Snyder, P. W., Gill, L. J., & Heldreth, B. (2019). Safety Assessment of Glycerin as Used in Cosmetics. *International Journal of Toxicology*, 38(3_suppl), 6S-22S. <https://doi.org/10.1177/1091581819883820>
- Belousov, A. S. (2021). Tuning of Selectivity for Sustainable Production of Acrolein from Glycerol. *ChemistrySelect*, 6(34), 9191–9198. <https://doi.org/10.1002/slct.202102547>
- Bhowmik, A., Kumar, R., Thulasiram, R., A, K., Thatoi, D. N., Bisht, Y. S., Samal, P., Kottedda, T. K., Tejani, G. G., & Santhosh, A. J. (2025). A comprehensive review on the viability of minimum quantity lubrication technology for machining difficult-to-cut alloys. *AIP Advances*, 15(3), 030702. <https://doi.org/10.1063/5.0256932>
- Björling, M., & Shi, Y. (2019). DLC and Glycerol: Superlubricity in Rolling/Sliding Elastohydrodynamic Lubrication. *Tribology Letters*, 67(1), 23. <https://doi.org/10.1007/s11249-019-1135-1>
- Candane, D., Alagumurthi, N., & Palaniradja, K. (2013). Tribological Studies on Deep Cryogenic Treated Aisi T42 High Speed Steel Using Response Surface Methodology. *Advances in Materials*, 2(2), 12–22. <https://doi.org/10.11648/j.am.20130202.11>
- Castelló, M., Dweck, J., & Aranda, D. (2009). Thermal stability and water content determination of glycerol by thermogravimetry. *Journal of Thermal Analysis and Calorimetry*, 97(2), 627–630. <https://doi.org/10.1007/s10973-009-0070-z>
- Chen, Z., Liu, Y., Zhang, S., & Luo, J. (2013). Controllable Superlubricity of Glycerol Solution via Environment Humidity. *Langmuir*, 29(38), 11924–11930. <https://doi.org/10.1021/la402422h>
- Ciriminna, R., Pina, C. D., Rossi, M., & Pagliaro, M. (2014). Understanding the glycerol market. *European Journal of Lipid Science and Technology*, 116(10), 1432–1439. <https://doi.org/10.1002/ejlt.201400229>
- Condotta, R., Gomes, E. L., de Freitas, D. A., & Poco, J. G. R. (2025). Acrolein Production from Glycerol: A Systematic Investigation of Metal-Oxides and Zeolite Catalysts. *Industrial & Engineering Chemistry Research*, 64(8), 4300–4308. <https://doi.org/10.1021/acs.iecr.4c04126>
- Consolidated TEXT: 32018D1702 — EN — 20.12.2024. (n.d.). Retrieved November 10, 2025, from <https://eur-lex.europa.eu/eli/dec/2018/1702/2024-12-20/eng>
- D02 Committee. (n.d.). *Test Method for Wear Preventive Characteristics of Lubricating Fluid (Four-Ball Method)*. ASTM International. <https://doi.org/10.1520/D4172-21>
- de Sousa, J. A. G., Sales, W. F., & Machado, A. R. (2018). A review on the machining of cast irons. *The International Journal of Advanced Manufacturing Technology*, 94(9), 4073–4092. <https://doi.org/10.1007/s00170-017-1140-1>
- Deja, M., Siemiątkowski, M., & Sender, P. (2017). COMPARATIVE STUDY OF MACHINING TECHNOLOGY SELECTION TO MANUFACTURE LARGE-SIZE COMPONENTS OF

- OFFSHORE CONSTRUCTIONS. *Polish Maritime Research*, 24(S1(93)), 38–45. <https://doi.org/10.1515/pomr-2017-0019>
- Demmerling, A. L. (2023). *Qualification of Metalworking Fluids by Tapping Torque Tests and Related Acoustic Emission-based Classifications*. Universität Duisburg-Essen.
- Di Martino, P. (2021). Ways to improve biocides for metalworking fluid. *AIMS Microbiology*, 7(1), 13–27. <https://doi.org/10.3934/microbiol.2021002>
- Directive—2008/98—EN - Waste framework directive—EUR-Lex. (n.d.). Retrieved October 3, 2025, from <https://eur-lex.europa.eu/eli/dir/2008/98/oj/eng>
- dos Santos, A. G., De Oliveira, D., Gomes, M. C., Jackson, M. J., & da Silva, M. B. (2025). Correlation between tool wear and machining temperature in micromilling of Ti-6Al-4V alloy. *Wear*, 571, 205793. <https://doi.org/10.1016/j.wear.2025.205793>
- Duan, Z., Wang, Z., Wang, S., Zhang, B., Bian, P., Li, Y., Liu, J., Song, J., Li, C., & Liu, X. (2025). Tool wear in enhanced minimum quantity lubrication assisted milling: From mechanism to application. *Chinese Journal of Aeronautics*, 103597. <https://doi.org/10.1016/j.cja.2025.103597>
- European Court of Auditors. (2023). *EU actions to address the increasing amount of hazardous waste*. Publications Office of the European Union. <https://data.europa.eu/doi/10.2865/519218>
- Fernando, J. T., & Siani, S. R. (2016). Renewable Energy Sources in Developing Countries: Challenges and Opportunities for a Sustainable Development Agenda. *Journal on Innovation and Sustainability RISUS*, 7(1), 64–71. <https://doi.org/10.24212/2179-3565.2016v7i1p64-71>
- Fernando, W. L. R., Karunathilake, H. P., & Gamage, J. R. (2021). Strategies to reduce energy and metalworking fluid consumption for the sustainability of turning operation: A review. *Cleaner Engineering and Technology*, 3, 100100. <https://doi.org/10.1016/j.clet.2021.100100>
- Ferreira, A. G. M., Egas, A. P. V., Fonseca, I. M. A., Costa, A. C., Abreu, D. C., & Lobo, L. Q. (2017). The viscosity of glycerol. *The Journal of Chemical Thermodynamics*, 113, 162–182. <https://doi.org/10.1016/j.jct.2017.05.042>
- Fischer, C. (n.d.). *About the Thermal Stability of Glycerol Investigation of High-Boiling Organics by TGA-FT-IR*. Retrieved November 12, 2025, from https://analyzing-testing.netzsch.com/_Resources/Persistent/9/9/0/d/990d4a0f6db3661828fa92806cf5511e8962a707/AN%20270_About%20the%20Thermal%20Stability%20of%20Glycerol.pdf
- Fisher, T. R., Zhou, G., Shi, Y., & Huang, L. (2020). How does hydrogen bond network analysis reveal the golden ratio of water–glycerol mixtures? *Physical Chemistry Chemical Physics*, 22(5), 2887–2907. <https://doi.org/10.1039/C9CP06246G>
- Ganesh, S., Harish, B., Shashank, V., Akash, S., & Harish, B. (2023). Performance evaluation of glycerol and coconut oil added cutting fluid in EN31 turning process. *Materials Today: Proceedings*. <https://doi.org/10.1016/j.matpr.2023.11.147>
- Ghugre, N. C., & Palande, D. D. (2024). Investigating the influence of cutting fluid on tool life and power usage during AISI-4130 steel turning. *Frontiers in Engineering and Built Environment*, 5(1), 22–39. <https://doi.org/10.1108/FEBE-07-2024-0035>
- Glycerol price index*. (2025, July 29). Businessanalytiq. <https://businessanalytiq.com/procurementanalytics/index/glycerol-price-index/>
- Gonçalves, D., Bozzi Barbeiro, L., Tonon de Souza, P., Caldas Batista, E. A., & de Almeida Meirelles, A. J. (2022). Thermal stability of glycerol containing compounds from the biodiesel production chain. *Journal of Thermal Analysis and Calorimetry*, 147(21), 11857–11874. <https://doi.org/10.1007/s10973-022-11395-4>
- Green, B. N., Johnson, C. D., & Adams, A. (2006). Writing narrative literature reviews for peer-reviewed journals: Secrets of the trade. *Journal of Chiropractic Medicine*, 5(3), 101–117. [https://doi.org/10.1016/S0899-3467\(07\)60142-6](https://doi.org/10.1016/S0899-3467(07)60142-6)
- Greenhalgh, T., Thorne, S., & Malterud, K. (2018). Time to challenge the spurious hierarchy of systematic over narrative reviews? *European Journal of Clinical Investigation*, 48(6), e12931. <https://doi.org/10.1111/eci.12931>
- Guo, Q. (2023). Reviews on the machining and measurement of large components. *Advances in Mechanical Engineering*, 15(9), 16878132231191381. <https://doi.org/10.1177/16878132231191381>
- Gupta, M. K., Nieslony, P., Korkmaz, M. E., Kuntoğlu, M., Królczyk, G. M., Günay, M., & Sarikaya, M. (2023). Comparison of Tool Wear, Surface Morphology, Specific Cutting Energy and Cutting Temperature in Machining of Titanium Alloys Under Hybrid and Green Cooling Strategies. *International Journal*

- of Precision Engineering and Manufacturing-Green Technology*, 10(6), 1393–1406. <https://doi.org/10.1007/s40684-023-00512-9>
- Hazardous Waste Companies in UK: Collection, Disposal, Costs. (n.d.). <https://Inspirewaste.Co.Uk/>. Retrieved October 3, 2025, from <https://inspirewaste.co.uk/hazardous-waste-companies-in-the-uk-regulation-collection-disposal-costs/>
- Hazardous Waste Disposal Price List | opasnite.bg. (n.d.). <https://Opasnite.Bg/>. Retrieved October 3, 2025, from <https://opasnite.bg/en/price-list/>
- Huang, L., Wang, B., Liu, L., & Borgna, A. (2023). Liquid-Phase Dehydration of Glycerol to Acrolein with ZSM-5-Based Catalysts in the Presence of a Dispersing Agent. *Molecules*, 28(8), 3316. <https://doi.org/10.3390/molecules28083316>
- Huang, S., Dong, T., Jiang, G., Yang, J., Yang, X., & Wang, Q. (2024). Synthesis and Performance Evaluation of High-Temperature-Resistant Extreme-Pressure Lubricants for a Water-Based Drilling Fluid Gel System. *Gels*, 10(8), 505. <https://doi.org/10.3390/gels10080505>
- ISO 6743-7:1986. (n.d.). ISO. Retrieved November 10, 2025, from <https://www.iso.org/standard/13216.html>
- Jaegers, N. R., Hu, W., Weber, T. J., & Hu, J. Z. (2021). Low-temperature (< 200 °C) degradation of electronic nicotine delivery system liquids generates toxic aldehydes. *Scientific Reports*, 11(1), 7800. <https://doi.org/10.1038/s41598-021-87044-x>
- Jemielniak, K. (2021). Review of new developments in machining of aerospace materials. *Journal of Machine Engineering*, 22–55. <https://doi.org/10.36897/jme/132905>
- Johnston, M., & Holloway, T. (2007). A Global Comparison of National Biodiesel Production Potentials. *Environmental Science & Technology*, 41(23), 7967–7973. <https://doi.org/10.1021/es062459k>
- Kächele, M., Monakhova, Y. B., Kuballa, T., & Lachenmeier, D. W. (2014). NMR investigation of acrolein stability in hydroalcoholic solution as a foundation for the valid HS-SPME/GC-MS quantification of the unsaturated aldehyde in beverages. *Analytica Chimica Acta*, 820, 112–118. <https://doi.org/10.1016/j.aca.2014.02.030>
- Katryniok, B., Paul, S., Capron, M., & Dumeignil, F. (2009). Towards the Sustainable Production of Acrolein by Glycerol Dehydration. *ChemSusChem*, 2(8), 719–730. <https://doi.org/10.1002/cssc.200900134>
- Kazimierowicz, J., Dębowski, M., Zieliński, M., Kasiński, S., & Cruz Sanchez, J. (2024). Biotechnological Valorization of Waste Glycerol into Gaseous Biofuels—A Review. *Energies*, 17(2), Article 2. <https://doi.org/10.3390/en17020338>
- Kenar, J. A. (2007). Glycerol as a platform chemical: Sweet opportunities on the horizon? *Lipid Technology*, 19(11), 249–253. <https://doi.org/10.1002/lite.200700079>
- Kirici, E. Y., Anzizi, S., Park, J., & Higgins, D. (2024). Electrochemical Conversion of Low-Cost Glycerol to Valuable Products. *ECS Meeting Abstracts*, MA2024-01(56), 2969. <https://doi.org/10.1149/MA2024-01562969mtgabs>
- Klocke, F., Gierlings, S., Brockmann, M., & Veselovac, D. (2011). Influence of Temperature on Surface Integrity for Typical Machining Processes in Aero Engine Manufacture. *Procedia Engineering*, 19, 203–208. <https://doi.org/10.1016/j.proeng.2011.11.102>
- Koch, T. (2023). Microbiology of Metalworking Fluids: What We Know and Lessons to be Learnt. *Acta Mechanica et Automatica*, 17(2), 166–172. <https://doi.org/10.2478/ama-2023-0018>
- Krajnik, P., Hashimoto, F., Karpuschewski, B., da Silva, E. J., & Axinte, D. (2021). Grinding and fine finishing of future automotive powertrain components. *CIRP Annals*, 70(2), 589–610. <https://doi.org/10.1016/j.cirp.2021.05.002>
- Kuczmaszewski, J., Zagórski, I., & Zgórnjak, P. (2022). Chip Temperature Measurement in the Cutting Area During Rough Milling Magnesium Alloys with a Kordell Geometry End Mill. *Advances in Science and Technology Research Journal*, 16(2), 109–119. <https://doi.org/10.12913/22998624/146851>
- Kumar, A., Thakur, A. K., Gaurav, G. K., Klemeš, J. J., Sandhwar, V. K., Pant, K. K., & Kumar, R. (2023). A critical review on sustainable hazardous waste management strategies: A step towards a circular economy. *Environmental Science and Pollution Research International*, 30(48), 105030–105055. <https://doi.org/10.1007/s11356-023-29511-8>
- Kwon, K. C., & Pallerla, S. (2000). Viscosity of Glycerol and Its Aqueous Solutions Measured by a Tank-Tube Viscometer. *Chemical Engineering Communications*, 183(1), 71–97. <https://doi.org/10.1080/00986440008960503>
- Latinović, L. (2021). Glycerol-based Metalworking Fluids. *Proceedings of III International Scientific and Professional Conference on Circular and Bioeconomics*, 140–150.

- Latinović, L., & Marjanović, M. (2021). A systematic review of human health risks associated with metalworking fluids exposure. *Serbian Journal of Engineering Management*, 6(2), 1–10. <https://doi.org/10.5937/SJEM2102001L>
- Latinović, L., Stojić, N., & Latinović, J. (2020). Important factors in the revival of the biodiesel industry in Serbia: Progress or pitfall? *Serbian Journal of Engineering Management*, 5(2), 1–19. <https://doi.org/10.5937/SJEM2002001L>
- Leiden, A., Arafat, R., Callegari, M., Kolb, M., Herrmann, C., & Wichmann, H. (2023). Development and testing of novel mineral oil- and biocide-free glycerol- and propanediol-based fluids for drilling and tapping aluminium alloys. *The International Journal of Advanced Manufacturing Technology*, 126(5), 2323–2336. <https://doi.org/10.1007/s00170-023-11283-7>
- Liu, J., Zhao, X., Wang, W., Yan, Y., Huang, G., Liang, M., Feng, X., & Ji, W. (2025). Acrolein production from glycerol dehydration over amorphous V–P–N–C catalysts. *RSC Advances*, 15(13), 9801–9809. <https://doi.org/10.1039/D4RA08613A>
- Liu, L., Yu, F., Wang, S., & Ye, X. P. (2023). Glycerol Dehydration to Acrolein Catalyzed by Silicotungstic Acid: Effect of Mesoporous Support. *Eng*, 4(1), 206–222. <https://doi.org/10.3390/eng4010012>
- Liu, Y., Zhong, B., & Lawal, A. (2022). Recovery and utilization of crude glycerol, a biodiesel byproduct. *RSC Advances*, 12(43), 27997–28008. <https://doi.org/10.1039/D2RA05090K>
- Long, Y., Bouchet, M.-I. D. B., Lubrecht, T., Onodera, T., & Martin, J. M. (2019). Superlubricity of glycerol by self-sustained chemical polishing. *Scientific Reports*, 9(1), 6286. <https://doi.org/10.1038/s41598-019-42730-9>
- Lopez, G., Farfan, J., & Breyer, C. (2022). Trends in the global steel industry: Evolutionary projections and defossilisation pathways through power-to-steel. *Journal of Cleaner Production*, 375, 134182. <https://doi.org/10.1016/j.jclepro.2022.134182>
- Ma, Q., Wang, W., & Dong, G. (2021). Achieving Macroscale Liquid Superlubricity Using Lubricant Mixtures of Glycerol and Propanediol. *Tribology Letters*, 69(4), 159. <https://doi.org/10.1007/s11249-021-01519-6>
- Mishra, S., & Aggarwal, S. (2023). A critical review of the effect of nano-lubricant on the performance of hydrodynamic journal bearing. *Tribologia - Finnish Journal of Tribology*, 40(4), 4–20. <https://doi.org/10.30678/ft.127785>
- Moklis, M. H., Cheng, S., & Cross, J. S. (2023). Current and Future Trends for Crude Glycerol Upgrading to High Value-Added Products. *Sustainability*, 15(4), 2979. <https://doi.org/10.3390/su15042979>
- Momeni, A., Moradi, S. S. T., & Tabatabaei-Nejad, S. A. (2024). A Review on Glycerol-Based Drilling Fluids and Glycerine as a Drilling Fluid Additive. *Rudarsko-Geološko-Naftni Zbornik*, 39(1), 87–99. <https://doi.org/10.17794/rgn.2024.1.8>
- Monteiro, M. R., Kugelmeier, C. L., Pinheiro, R. S., Batalha, M. O., & da Silva César, A. (2018). Glycerol from biodiesel production: Technological paths for sustainability. *Renewable and Sustainable Energy Reviews*, 88, 109–122. <https://doi.org/10.1016/j.rser.2018.02.019>
- Nowak, P., Kucharska, K., & Kamiński, M. (2019). Ecological and Health Effects of Lubricant Oils Emitted into the Environment. *International Journal of Environmental Research and Public Health*, 16(16), 3002. <https://doi.org/10.3390/ijerph16163002>
- OECD & Food and Agriculture Organization of the United Nations. (2013). *OECD-FAO Agricultural Outlook 2013*. OECD. https://doi.org/10.1787/agr_outlook-2013-en
- OECD-FAO *Agricultural Outlook 2023-2032*. (2023, July 6). OECD. https://www.oecd.org/en/publications/oecd-fao-agricultural-outlook-2023-2032_08801ab7-en.html
- Okhiria, P., Björling, M., Johansson, P., Hasan, M., Larsson, R., & Shi, Y. (2024). Tribological Performance of Glycerol-Based Hydraulic Fluid Under Low-Temperature Conditions. *Lubricants*, 12(12), 430. <https://doi.org/10.3390/lubricants12120430>
- Oxford Economics. (2019). *The role of steel manufacturing in the global economy (Report)*. Oxford Economics. <https://worldsteel.org/wp-content/uploads/The-role-of-steel-manufacturing-in-the-global-economy.pdf>
- Pape, F., Poll, G., Ellersieck, L., Denkena, B., & Liu, H. (2023). Tribological Effects of Metalworking Fluids in Cutting Processes. *Lubricants*, 11(5), 224. <https://doi.org/10.3390/lubricants11050224>
- Pauliuk, S., Milford, R. L., Müller, D. B., & Allwood, J. M. (2013). The Steel Scrap Age. *Environmental Science & Technology*, 47(7), 3448–3454. <https://doi.org/10.1021/es303149z>

- Pérez-Salinas, C., de Lacalle, L. N. L., del Olmo, A., & Kumar, C. S. (2024). The relationship between the cutting-edge, tool wear, and chip formation during Inconel 718 dry cutting. *The International Journal of Advanced Manufacturing Technology*, 132(11), 6001–6017. <https://doi.org/10.1007/s00170-024-13685-7>
- Ploumis, P. (n.d.). *Weekly Scrap Metal Price Report- July 4, 2025*. ScrapMonster. Retrieved October 3, 2025, from <https://www.scrapmonster.com/news/weekly-metal-price-report/weekly-scrap-metal-price-report-july-4-2025/96463>
- Raof, N. A., Hamid, H. A., Mohamad Aziz, N. A., & Yunus, R. (2022). Prospects of Plant-Based Trimethylolpropane Esters in the Biolubricant Formulation for Various Applications: A Review. *Frontiers in Mechanical Engineering*, 8. <https://doi.org/10.3389/fmech.2022.833438>
- Regulation—1272/2008—EN - *clp regulation*—EUR-Lex. (n.d.). Retrieved October 3, 2025, from <https://eur-lex.europa.eu/eli/reg/2008/1272/oj/eng>
- Rietdorf, C., Ziehn, S., Giunta, S. M., Mische, R., & Sauer, A. (2024). Environmental Assessment of Metal Chip Recycling – Quantification of Mechanical Processing’s Global Warming Potential. *Procedia CIRP*, 122, 241–246. <https://doi.org/10.1016/j.procir.2024.02.009>
- Ríos, F., Caparrós-Salvador, F., Lechuga, M., & Fernández-Serrano, M. (2024). Complete biodegradability assessment of polyoxyethylene glycerol ester non-ionic surfactant: Aerobic, anaerobic, combined biodegradation and inhibitory effects. *Water Research*, 248, 120857. <https://doi.org/10.1016/j.watres.2023.120857>
- Ruy, A. D. da S., Ferreira, A. L. F., Bresciani, A. É., Alves, R. M. de B., Pontes, L. A. M., Ruy, A. D. da S., Ferreira, A. L. F., Bresciani, A. É., Alves, R. M. de B., & Pontes, L. A. M. (2020). Market Prospecting and Assessment of the Economic Potential of Glycerol from Biodiesel. In *Biotechnological Applications of Biomass*. IntechOpen. <https://doi.org/10.5772/intechopen.93965>
- Santos, M. C., Machado, A. R., Sales, W. F., Barrozo, M. A. S., & Ezugwu, E. O. (2016). Machining of aluminum alloys: A review. *The International Journal of Advanced Manufacturing Technology*, 86(9), 3067–3080. <https://doi.org/10.1007/s00170-016-8431-9>
- Scrap Metal Price Index—Germany—Metaloop. (n.d.). Retrieved October 3, 2025, from <https://www.metaloop.com/scrap-metal-price/germany/>
- Shi, Y., Minami, I., Grahm, M., Björling, M., & Larsson, R. (2014). Boundary and elastohydrodynamic lubrication studies of glycerol aqueous solutions as green lubricants. *Tribology International*, 69, 39–45. <https://doi.org/10.1016/j.triboint.2013.08.013>
- Shokrani, A., Arrazola, P. J., Biermann, D., Mativenga, P., & Jawahir, I. S. (2024). Sustainable machining: Recent technological advances. *CIRP Annals*, 73(2), 483–508. <https://doi.org/10.1016/j.cirp.2024.06.001>
- Stevens, J. F., & Maier, C. S. (2008). Acrolein: Sources, metabolism, and biomolecular interactions relevant to human health and disease. *Molecular Nutrition & Food Research*, 52(1), 7–25. <https://doi.org/10.1002/mnfr.200700412>
- Sukhera, J. (2022). Narrative Reviews: Flexible, Rigorous, and Practical. *Journal of Graduate Medical Education*, 14(4), 414–417. <https://doi.org/10.4300/JGME-D-22-00480.1>
- Takamura, K., Fischer, H., & Morrow, N. R. (2012). Physical properties of aqueous glycerol solutions. *Journal of Petroleum Science and Engineering*, 98–99, 50–60. <https://doi.org/10.1016/j.petrol.2012.09.003>
- Tamayo, J. G. Z., Björling, M., Shi, Y., Prakash, B., & Larsson, R. (2022). Micropitting performance of glycerol-based lubricants under rolling-sliding contact conditions. *Tribology International*, 167, 107348. <https://doi.org/10.1016/j.triboint.2021.107348>
- Thakur, A., & Gangopadhyay, S. (2016). State-of-the-art in surface integrity in machining of nickel-based super alloys. *International Journal of Machine Tools and Manufacture*, 100, 25–54. <https://doi.org/10.1016/j.ijmactools.2015.10.001>
- Thayyil Raju, L., Diddens, C., Li, Y., Marin, A., van der Linden, M. N., Zhang, X., & Lohse, D. (2022). Evaporation of a Sessile Colloidal Water–Glycerol Droplet: Marangoni Ring Formation. *Langmuir*, 38(39), 12082–12094. <https://doi.org/10.1021/acs.langmuir.2c01949>
- Tomatis, M., Kumar Jeswani, H., & Azapagic, A. (2024). Environmental impacts of valorisation of crude glycerol from biodiesel production – A life cycle perspective. *Waste Management*, 179, 55–65. <https://doi.org/10.1016/j.wasman.2024.03.005>
- Trajkovski, A., Novak, N., Pustavrh, J., Kalin, M., & Majdič, F. (2023). Performance of Polymer Composites Lubricated with Glycerol and Water as Green Lubricants. *Applied Sciences*, 13(13), 7413. <https://doi.org/10.3390/app13137413>

- Ulutan, D., & Ozel, T. (2011). Machining induced surface integrity in titanium and nickel alloys: A review. *International Journal of Machine Tools and Manufacture*, 51(3), 250–280. <https://doi.org/10.1016/j.ijmactools.2010.11.003>
- Uriarte, L., Zatarain, M., Axinte, D., Yagüe-Fabra, J., Ihlenfeldt, S., Eguia, J., & Olarra, A. (2013). Machine tools for large parts. *CIRP Annals*, 62(2), 731–750. <https://doi.org/10.1016/j.cirp.2013.05.009>
- Verma, V., & Yadav, N. (2024). Effect of plant extracts on the reduction of acrylamide and hydroxymethylfurfural formation in French fries. *Food Chemistry Advances*, 4, 100708. <https://doi.org/10.1016/j.focha.2024.100708>
- Walker, T. (2015). *Minimum Quantity Lubrication*.
- Weeraratna, C., Amarasinghe, C., Lu, W., & Ahmed, M. (2021). A Direct Probe of the Hydrogen Bond Network in Aqueous Glycerol Aerosols. *The Journal of Physical Chemistry Letters*, 12(23), 5503–5511. <https://doi.org/10.1021/acs.jpcllett.1c01383>
- Wichmann, H., Stache, H., Schmidt, C., Winter, M., Bock, R., Herrmann, C., & Bahadir, M. (2013). Ecological and economic evaluation of a novel glycerol based biocide-free metalworking fluid. *Journal of Cleaner Production*, 43, 12–19. <https://doi.org/10.1016/j.jclepro.2012.12.042>
- Winter, M., Bock, R., Herrmann, C., Stache, H., Wichmann, H., & Bahadir, M. (2012). Technological evaluation of a novel glycerol based biocide-free metalworking fluid. *Journal of Cleaner Production*, 35, 176–182. <https://doi.org/10.1016/j.jclepro.2012.05.048>
- World Steel in Figures 2022. (n.d.). *Worldsteel.Org*. Retrieved October 3, 2025, from <https://worldsteel.org/data/world-steel-in-figures/world-steel-in-figures-2022/>
- Wright, T. P., Song, C., Sears, S., & Petters, M. D. (2016). Thermodynamic and kinetic behavior of glycerol aerosol. *Aerosol Science and Technology*, 50(12), 1385–1396. <https://doi.org/10.1080/02786826.2016.1245405>
- Yawara, P., & Intanon, N. (2019). A Comparative study of Wear and tool life of HSS TiN coated end mills and WC uncoated end mills. *MATEC Web of Conferences*, 264, 01006. <https://doi.org/10.1051/mateconf/201926401006>
- Yi, X., Xu, H., Jin, G., Lu, Y., Chen, B., Xu, S., Shi, J., & Fan, X. (2024). Boundary slip and lubrication mechanisms of organic friction modifiers with effect of surface moisture. *Friction*, 12(7), 1483–1498. <https://doi.org/10.1007/s40544-023-0820-0>
- Yurtkuran, H., Günay, M., & Rai, R. (2024). A State of the Art on Sustainable Metal Working Fluids in Machining Applications. *Journal of Molecular and Engineering Materials*, 12(03), 2440013. <https://doi.org/10.1142/S2251237324400136>
- Zhang, D., Cao, Y., Zhang, P., Liang, J., Xue, K., Xia, Y., & Qi, Z. (2021). Investigation of the thermal decomposition mechanism of glycerol: The combination of a theoretical study based on the Minnesota functional and experimental support. *Physical Chemistry Chemical Physics*, 23(36), 20466–20477. <https://doi.org/10.1039/D1CP01526E>