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Beyond Waste Valorization: Glycerol-Based Metalworking Fluids as Hephaestus for the Circular Economy and Sustainability Transitions

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Abstract: Rapid expansion of biodiesel production has generated large streams of low-value crude glycerol, whose role in industrial systems is partially explored. Since this stream is a by-product of policy-driven renewable energy and simultaneously a burden of waste management, its use as a metalworking fluids (MWFs) base stock provides a direct test of whether the transition of energy could be translated into cleaner manufacturing rather than impact shifting. This paper examined whether deploying glycerol-based MWFs in machining could reconfigure waste flows and occupational exposures, to be in line with circular economy and industrial-ecology principles, and under what conditions this could support sustainability transitions. Using a critical narrative review of technical, environmental, and policy literature, we synthesized evidence on the performance of glycerol as a base fluid and the system-level constraints that governed its adoption. The synthesis suggested that, in suitable machining regimes and under enforceable governance conditions, prospective gains included the reclassification of metallic residues from hazardous to non-hazardous streams and improved occupational safety by reducing reliance on biocides and volatile organic compounds. These prospective gains were conditional: adoption was constrained by thermal instability, possible acrolein formation at elevated temperatures, and inconsistent feedstock quality. The paper therefore offered a transdisciplinary synthesis connecting technical performance, waste-classification regimes, and governance instruments. The derived policy needs covered the minimum impurity specifications for industrial glycerol, clearer waste-coding guidance for swarf and spent fluids, and incentives for monitoring and process adaptation to secure net sustainability benefits. In this connection, Hephaestus serves as a metaphor for glycerol-based MWFs: a marginal by-product that could rework glycerol and metallic residues into useful resources, when technical optimization and institutional coordination (including standards and partnerships aligned with SDG 17) are in place.

Keywords: Biodiesel; Metalworking fluids; Swarf; Industrial symbiosis; Governance; SDG 17

1. Introduction

Contemporary industrial societies face intensifying environmental pressures that demand structural transformations in the production and consumption systems (Wang & Azam, 2024). Industrial activities, while foundational to economic growth, contribute largely to greenhouse gas emissions, resource depletion, and waste generation. To address these challenges, the discourse of sustainability has shifted from incremental improvements in eco-efficiency toward systemic industrial transitions, i.e., transformations that involve the reconfiguration of technologies, infrastructures, regulations, and social practices (Geels et al., 2023; Moallemi et al., 2025). Manufacturing is central in this regard because it concentrates material and energy use and generates large and technology-dependent waste streams. Within manufacturing, metalworking underpins key value chains such as automotive, aerospace, energy and construction, but also produces substantial quantities of contaminated swarf and exposes workers to process fluids (Latinović & Marjanović, 2021). Pursuing sustainable metalworking therefore requires more than reductions in energy intensity. Other prerequisites include redesigning material and resource flows along circular economy, industrial ecology, and extended producer-responsibility principles

(Dennison et al., 2024) such as re-evaluating the role of metalworking fluids (MWFs) in shaping waste and exposure profiles. In this context, surplus crude glycerol, an abundant biodiesel by-product, and challenge to waste management, offers a strategic feedstock for MWF reformulation and its associated redesign of the waste pathway. Against this background, the paper treated crude glycerol as a coupling point between the renewable-energy transition and cleaner manufacturing, using MWFs as a leverage point that shaped both occupational exposure and the contamination and regulatory status of metal residues. The review addressed a gap in the fragmented literature by linking the limits of technical performance and impurity variability to the outcomes of circular economy, and to the policy and standardization conditions needed for net sustainability gains at scale.

1.1 Oversupply of Glycerol and Opportunities of Circular Economy

Over the past two decades, policies of biodiesel have created persistent streams of crude glycerol that run parallel to fuel supply chains. Typically accounting for around 10% of the mass output of transesterification, this co-product accumulates at a pace that exceeds the absorptive capacity of conventional markets and niche chemical uses (Attarbachi et al., 2023; Ben et al., 2022; Latinović et al., 2020). Rather than a simple issue of price depression, this situation reveals a structural mismatch between the deployment of renewable energy and the material cycles in which its by-products are embedded. When crude glycerol is channeled primarily into low-value outlets, such as bulk combustion or marginal chemical conversions, the biofuel chain reproduces a linear logic of "take–make–dispose" and externalizes the costs of surplus management (Attarbachi et al., 2023; Tomatis et al., 2024). Circular-economy thinking reframes this misalignment as a design failure: industrial systems should be configured so that such streams are anticipated as inputs to other processes. Integrating glycerol into applications that currently rely on fossil-derived materials, such as MWFs, thus becomes less a matter of opportunistic valorization and more a concrete test of whether circularity can be operationalized at the interface between energy and manufacturing sectors.

1.2 The Metalworking Sector as a Critical Node

Metalworking-intensive value chains form a backbone of contemporary manufacturing, to supply components to automotive, heavy machinery, aerospace, energy and construction industries worldwide (Yu & Li, 2023). Yet the practices that underpin this productivity remain tightly coupled to environmental and occupational burdens. Conventional MWFs, formulated predominantly from mineral oils and synthetic additives, generate toxic waste streams, expose workers to hazardous substances, and incur substantial end-of-life management costs (Latinović & Marjanović, 2021; Park, 2019; Thornéus et al., 2021). Once metallic swarf becomes impregnated with biocidal emulsions, it is frequently classified as hazardous waste within the European Union (EU) and national regulatory frameworks, which blocks access to standard recycling routes and requires specialized treatment (European Union, 2008). These path-dependent practices lock in a pattern of resource loss and escalating disposal expenditures that runs counter to the expectations of resource efficiency now placed on sustainable manufacturing systems (Ottink et al., 2022). In parallel, sustained exposure to petroleum fractions, or formaldehyde-releasing and isothiazolinone biocides is still linked to respiratory and dermatological disorders among machine operators, thus highlighting persistent tensions between production goals, occupational justice, and long-term health protection (Cammalleri et al., 2022; Nett et al., 2021; Silva et al., 2020).

1.3 Glycerol as a Bridge Between Renewable and Industrial Systems

The integration of glycerol into MWF formulations presents an innovative response that connects two distinct sustainability agendas: utilization of renewable energy by-product and clean production in manufacturing (Leiden et al., 2023; Wichmann et al., 2013; Winter et al., 2012). In parallel with broader efforts to design more benign MWFs (Khan et al., 2022; Sahai et al., 2024; Winter et al., 2012), glycerol stands out because its physicochemical profile aligns with several key performance and safety requirements. Its biodegradability (Benitez et al., 2024; Raghunandan et al., 2014), low-toxicity to humans (Akinsulie et al., 2025; Becker et al., 2019), biostatic behavior at sufficient concentration (Nalawade et al., 2015; Saegeman et al., 2008; Winter et al., 2012), corrosion-mitigating properties (Khlopyk et al., 2024; Palcut et al., 2023; Zubaidi et al., 2018), and favorable lubricity under boundary conditions (De Barros Bouchet et al., 2007; Qin et al., 2022; Sivebæk & Jakobsen, 2016) collectively position it as a promising base fluid in metalworking. When applied in machining operations, glycerol-based systems can sustain lubrication and surface quality (Fernandes et al., 2017; Leiden et al., 2023; Wichmann et al., 2013; Winter et al., 2012) as well as minimizing the need for toxic additives. This, in turn, reduces the chemical contamination of metal chips and opens the door for reclassifying swarf from hazardous waste to recyclable secondary raw material (Figure 1).

Enabling such reclassification has ramifications beyond individual workshops. It facilitates the return of high-quality metallic fractions to routes of secondary production, decreases reliance on primary ore extraction, and supports the closure of material loops in line with the European Circular Economy Action Plan. Meanwhile, less toxic process fluids reduce the regulatory and financial burden associated with the handling of hazardous waste, thus creating a more favorable context for aligning industrial practice with emergent circularity and zero-pollution agendas.

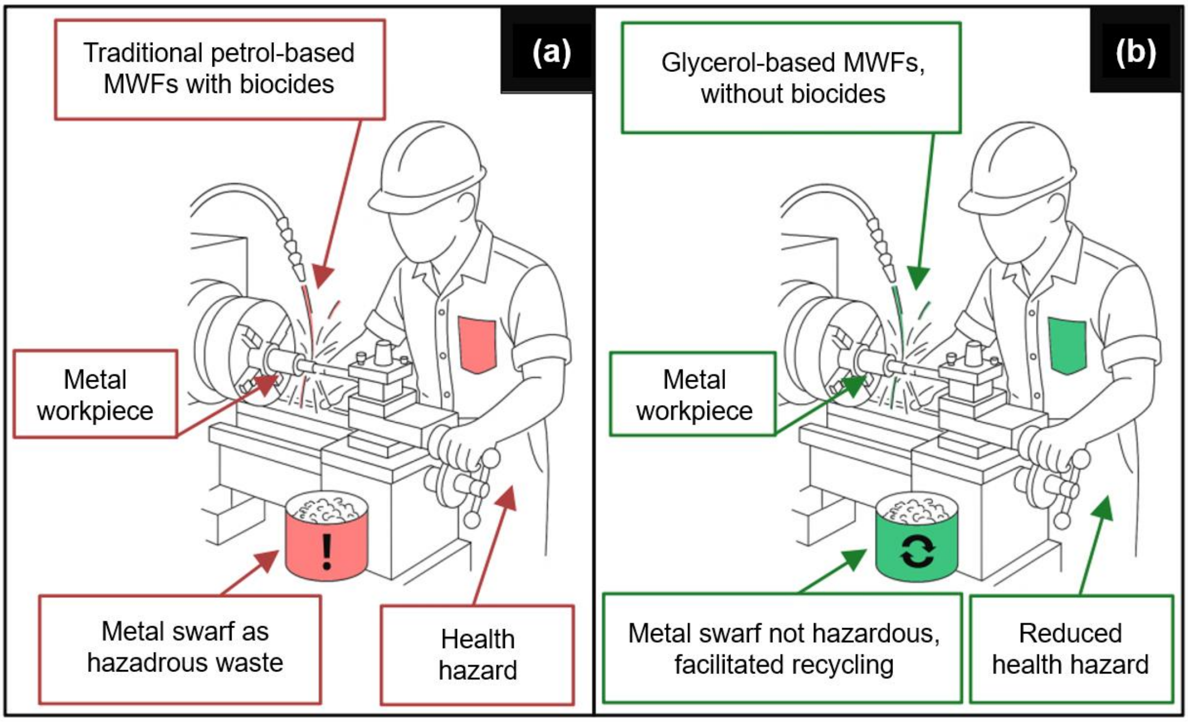

Figure 1. Comparative illustration of machining processes using (a) conventional petroleum-based metalworking fluids (MWFs) containing biocides, and (b) glycerol-based biocide-free MWFs

1.4 From Technical Innovation to Systemic Transition

Although laboratory and pilot-scale studies have demonstrated that glycerol-based fluids could achieve technically acceptable performance in selected machining regimes, the more consequential question is how such innovations interact with broader transition dynamics. New fluid formulations do not automatically translate into large-scale environmental or social benefits; their impact depends on how they are embedded within corporate strategies, industrial routines, and institutional arrangements. However, the literature rarely translated laboratory performance claims into governance-relevant system conditions such as specifications of impurity, waste-coding implications for swarf, and occupational risk controls, so the benefits of circular economy remain uncertain beyond niche adoption. Realizing the potential of glycerol-based MWFs therefore requires attention to the alignment of policy instruments, standardization efforts, market incentives, and occupational health frameworks with long-term sustainability objectives. In this perspective, glycerol serves not merely as a substitute lubricant, but as an analytical entry point for examining how industrial systems might reconfigure towards greater circularity, resilience, and equity.

The objective of this study is to critically assess how glycerol-based MWFs can contribute to sustainable industrial transitions through waste valorization and circular manufacturing practices. The analysis is organized around three interrelated research questions:

(1) How does the integration of glycerol-based fluids reshape the environmental and occupational dimensions of metalworking?

(2) Which systemic limitations and trade-offs arise when their use is scaled beyond experimental settings?

(3) What governance and policy arrangements are needed for glycerol to function as a transformative sustainability lever rather than remaining confined to niche applications?

To address these questions, the paper follows a stepwise structure aligned with a problem–benefit–risk–governance sequence. Section 2 establishes the integrated analytical lens (circular economy, industrial ecology, and sustainability transitions), and Section 3 describes the review approach. Section 4 synthesizes the expected benefits for cleaner manufacturing and circularity (waste and exposure implications). Section 5 evaluates risks and trade-offs that can offset these gains (thermal limits, degradation products such as acrolein, and impurity-driven variability and infrastructure constraints). Section 6 derives policy and standardization needs, including requirements of specification, waste-coding clarity, incentives, and occupational safeguards, under which glycerol-based MWFs can function as a transition lever rather than a niche substitute. Section 7 concludes the assessment in this paper.

2. Theoretical Framework

The integration of glycerol into metalworking systems can be interpreted through three complementary theoretical lenses within sustainability science: circular economy, industrial ecology, and sustainability transitions theory. Each framework highlights a different but mutually reinforcing dimension of systemic change.

2.1 Perspective of the Circular Economy

The circular economy seeks to decouple economic growth from depletion of resources by promoting reuse, recycling, and valorization of materials across industrial systems (Kara et al., 2022). In this paradigm, waste streams are reconsidered as secondary resources capable of re-entering production loops. The case of glycerol is emblematic of this principle. As a surplus by-product from biodiesel production (Bansod et al., 2024a), glycerol represents an underutilized renewable input (Moklis et al., 2023), whose incorporation into industrial metalworking could close material cycles between the energy and manufacturing sectors.

In operational terms, circular economy emphasizes design for circularity and industrial symbiosis (Birat, 2021). The adoption of glycerol-based MWFs aligns with both. It transforms an externally environmental burden into a productive input (symbiosis) and reduces downstream hazardous waste generation (circular design). This reconfiguration changes not only the material flow but also the institutional logic of production, hence linking the generation of renewable energy with sustainable manufacturing through tangible industrial exchanges.

2.2 Industrial Ecology and Efficiency of Systemic Resource

Industrial ecology extends beyond simple material substitution to encompass systemic metabolism, as well as the circulating flows of resources and energy in industrial networks. From this vantage, sustainability arises when industrial networks mimic ecological systems characterized by closed loops and minimal entropy. In that sense, glycerol valorization operationalizes this logic by channeling a by-product of one industrial metabolism (biofuel synthesis) into another (metalworking), thereby embedding circularity into real industrial flows (Burström et al., 2024; Chilakamarry et al., 2021; Ripoll & Betancor, 2021).

This integration produces secondary effects: reduced hazardous waste, improved occupational safety, and enhanced productivity of resources per unit of input. At the macro scale, it demonstrates how waste valorization strategies can contribute to achieving Sustainable Development Goals (SDGs) 12 (responsible consumption and production), 9 (industry, innovation, and infrastructure), and 17 (partnerships for the goals) which emphasizes the importance of capacity building, technology transfer, and policy coherence as enablers of sustainable development. Yet, industrial ecology also warns that such exchanges should be evaluated holistically, considering potential rebound effects, hidden emissions, or trade-offs between environmental and economic performance.

2.3 Sustainability Transitions and Governance Dimension

Sustainability transition theory emphasizes that technological solutions alone do not constitute transformation; change arises through multi-level interactions among innovations (niches), established systems (regimes), and sociopolitical environments (landscapes) (Harnesk, 2016; Kerkhoff, 2014; Köhler et al., 2019; Ovchynnykova et al., 2024). Glycerol-based MWFs currently exist as a niche innovation, technically feasible but not yet mainstream. Its diffusion depends on supportive governance, market incentives, and alignment with regulatory regimes governing waste, chemicals, and occupational safety. The transition pathway, therefore, requires policy orchestration rather than isolated technological deployment (Schandl et al., 2025). Public institutions could accelerate adoption by integrating bio-based lubricants into eco-design standards, fiscal incentives, and procurement frameworks. In parallel, industry associations and certification bodies could shape norms and performance benchmarks to ensure credibility and comparability. Without such coordination, the innovation risks remaining a marginal experiment as it is unable to overcome institutional lock-ins that favor conventional petroleum-based fluids (Altuntaş Vural & Aktepe, 2022; Simoens et al., 2022). Taken together, these perspectives form a joint analytical lens. Section 4 applies circular-economy and industrial-ecology principles to assess process-level impacts on waste and exposure. Section 5 combines industrial ecology with transition insights to interpret systemic trade-offs, impurity profiles, and lock-ins. Section 6 uses sustainability-transition theory to structure the analysis of governance, incentives, and policy coordination. Figure 2 illustrates how these perspectives converge into an integrated framework.

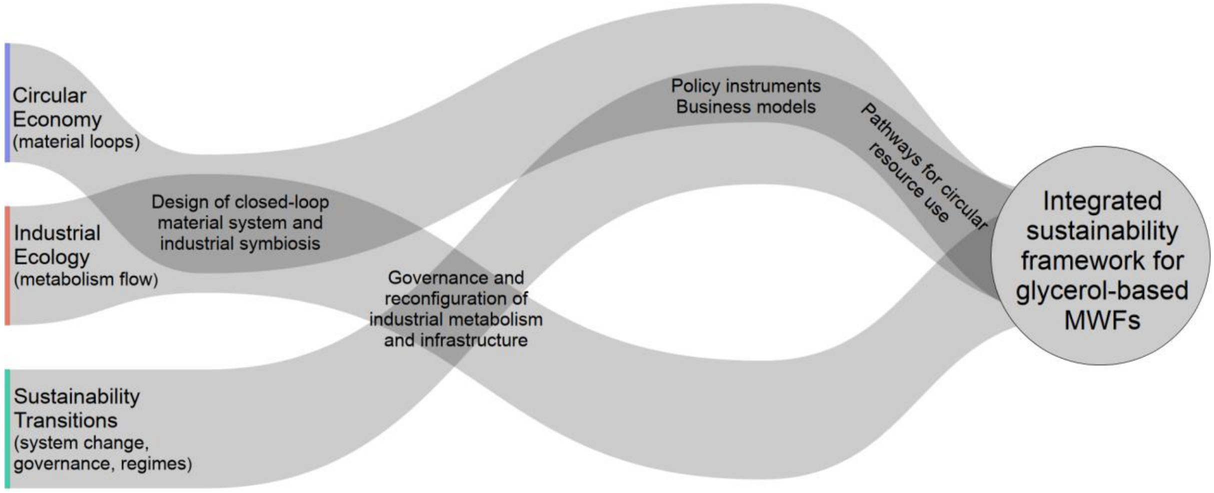

Figure 2. Interrelations among circular economy, industrial ecology, and sustainability transitions converging into an integrated sustainability framework for glycerol-based metalworking fluids (MWFs)

3. Methodology

This study employed a narrative literature review with a critical orientation, aimed not merely at summarizing existing findings but at interpreting them within the broader sustainability transition context. Unlike systematic reviews that prioritize methodological exhaustiveness (Snyder, 2019), a narrative design enables integration of heterogeneous evidence such as engineering performance data, evidence of environmental and occupational risks, and governance/policy instruments, while preserving analytical flexibility needed for transdisciplinary synthesis (Basheer, 2022; Sukhera, 2022). The design is well-suited for transdisciplinary research, such as this, where diverse data types must be synthesized to generate systemic insights rather than isolated technical conclusions.

3.1 Search and Selection Strategy

The literature search combined technical and systemic/policy keywords (e.g., “glycerol/glycerin/glycerine”, “metalworking fluids/MWF”, “thermal stability”, “acrolein”, “occupational exposure”, “waste classification”, “circular economy”, “waste valorization”, “sustainable manufacturing”, “industrial symbiosis”, and “policy transition”) to capture engineering, environmental, and governance perspectives. Searches were conducted across Google Scholar, Scopus, Web of Science, ScienceDirect, and EBSCO for 2006–2025, and were supplemented by targeted searches in institutional and grey literature to capture policy instruments, standards, and market-relevant evidence. Search strings were iteratively refined using alternative synonyms, truncations, and Boolean operators to balance recall and precision and to reduce the risk of missing cross-disciplinary links.

Inclusion criteria prioritized relevance to sustainability rather than methodological uniformity: (a) papers in which glycerol was analyzed as a component of metalworking or lubrication fluids; (b) works addressing environmental, occupational health, or waste-management implications of MWFs or lubricants; and (c) studies discussing industrial, regulatory, or policy frameworks relevant to adoption of bio-based process fluids. Exclusion criteria comprised studies focused exclusively on chemical synthesis of glycerol derivatives or biodiesel valorization pathways unless they provided transferable insights relevant to lubrication performance, waste valorization/classification, occupational risk, or governance implications.

Records were managed in Zotero. The initial search retrieved approximately 300 records. After de-duplication (≈50 removed), 252 titles/abstracts were screened; 66 records were excluded at this stage, and 186 full texts were assessed for eligibility. Full-text exclusions totaled 32 (reasons summarized in Figure 3), thus yielding a final evidence base of 154 distinct sources reconciled in Zotero and they were 128 peer-reviewed journal articles, 4 conference/proceedings items, 9 policy/standards/official reports (e.g., the EU/Organization for Economic Cooperation and Development (OECD)/Environmental Protection Agency (EPA)/Joint Research Centre (JRC)), 12 web pages or online datasets (e.g., price indices, market reports, and waste-code repositories), and 1 magazine/commentary source. The included sources were mapped (non-exclusively) into thematic evidence buckets to reflect the review structure: technical performance/process evidence (n = 33), environmental and waste implications (n = 25), occupational health/exposure evidence (n = 18), supply chain/purification/valorization including life-cycle assessment (LCA)/techno-economic analysis (TEA) (*n* = 29), and policy/governance evidence (*n* = 27), with additional general/contextual sources (*n* = 18).

Where high-quality systematic reviews or meta-analyses already synthesized, e.g., occupational exposure outcomes or feedstock variability, these were treated as anchors of secondary evidence and every primary study included in those syntheses was not re-screened unless a primary paper was directly required to support the narrative. To avoid double-counting, we cited the systematic syntheses for exposure–effect directions and used primary studies selectively, only when needed for parameter specificity or contextual comparability.

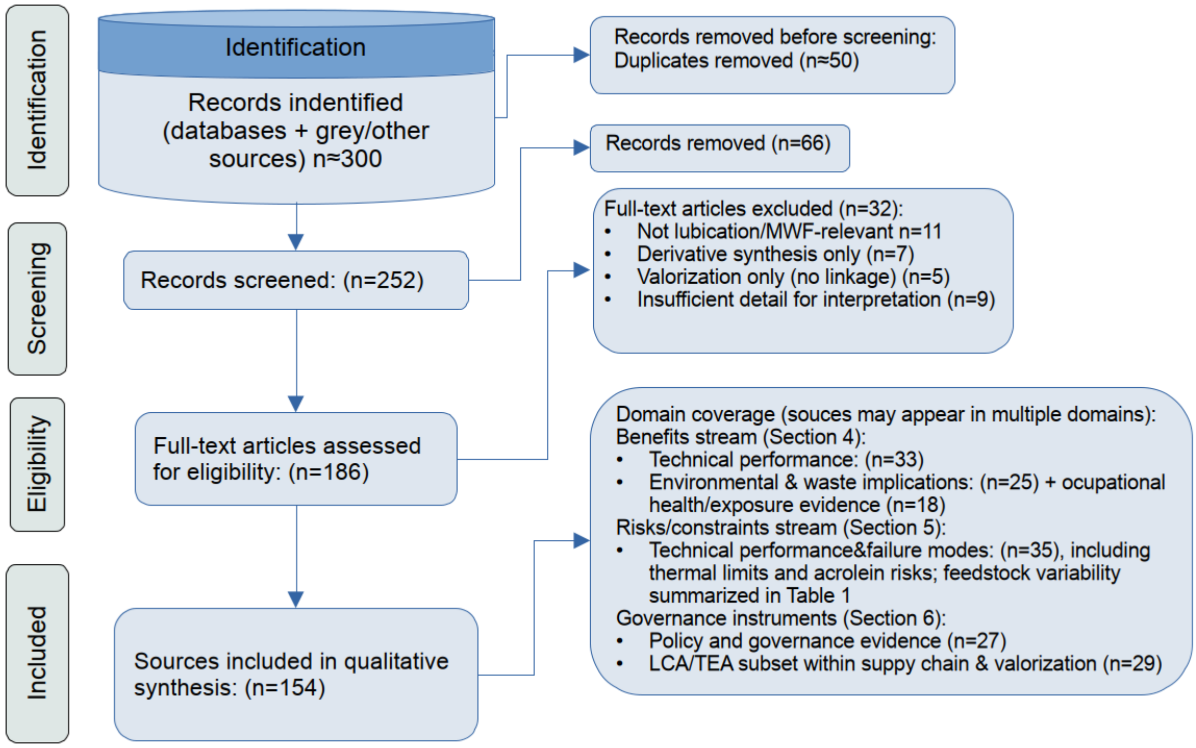

Figure 3. PRISMA flow diagram adapted for narrative review reporting

3.2 Analytical Procedure and Validity

Following the selection, the material was organized into three thematic clusters aligned with the analytical aims in this study: (1) environmental and occupational benefits; (2) technical and systemic constraints; and (3) industrial feasibility and governance implications. Each cluster was examined qualitatively to identify patterns of convergence and contradiction across sources, in order to link technical evidence (e.g., tribological, thermo-oxidative, and corrosion-relevant findings) to broader sustainability considerations such as waste classification and management, exposure control, and policy instruments for adoption. The analysis was guided by the integrative framework outlined in Section 2. Circular economy theory structured the interpretation of material and waste flows; industrial ecology framed efficiency and system-boundary implications, and sustainability transitions theory informed analysis of governance, instruments, and implementation barriers. Analytical validity was reinforced through triangulation across technical studies, life-cycle, techno-economic indications where available, and policy/market evidence, in order to prioritize internal consistency across heterogeneous types of sources.

3.3 Limitations of the Review

The narrative approach introduced subjectivity and reduced replicability through selective emphasis and heterogeneous evidence quality. However, given the objective in this paper, to interpret the potentially systemic role of glycerol in sustainable transformation of metalworking rather than to estimate pooled performance effects, this interpretive flexibility was aligned with the design of this study. Moreover, this review did not conduct a comparative LCA/TEA; thus, we reported screening-level quantitative anchors and treated "system-level" benefits as conditional on tool life, service interval, energy use, ventilation controls, and end-of-life handling parameters. Future work could complement these findings through empirical LCA, TEA, targeted occupational exposure measurement under glycerol-based fluids, and cross-sectoral policy evaluation to quantify trade-offs and conditions of implementation identified in this synthesis.

4. Environmental and Occupational Benefits

4.1 Environmental Compatibility and Biodegradability

One of the key sustainability advantages of glycerol lies in its relatively low environmental impact compared with mineral-oil-based fluids (Ben et al., 2022; Dekkers et al., 2025). As a trihydroxy alcohol of biological origin, glycerol is fully biodegradable under both aerobic and anaerobic conditions, in contrast to mineral oil–based fluids that persist in soil and aquatic environments (Bansod et al., 2024b; Becker et al., 2019; Dekkers et al., 2025). Its high microbial degradability suggests that post-use residues are less likely to persist in effluents or sludge, thereby potentially lowering the ecological footprint of metalworking operations.

This property directly supports the environmental goals articulated in the European Green Deal, UN SDG 12 (responsible production and consumption), and SDG 9 (sustainable industry and innovation). In practice, experimental studies indicate that replacing petroleum-based emulsions with glycerol-based formulations could reduce the total chemical oxygen demand (COD) of wastewater streams by approximately 30–60%, and lower effluent toxicity indices under controlled conditions (Chen et al., 2024; Muvel et al., 2025). The transition toward biodegradable fluids thus enables a measurable contribution to both corporate and policy-level sustainability metrics.

Beyond direct environmental metrics, glycerol substitution also aligns with principles of life-cycle optimization. The renewable origin of the fluid and its derivation from an existing industrial by-product mean that its environmental burden is already embedded in another process chain (Bansod et al., 2024a; Vanapalli et al., 2024). This co-product status may contribute to lowering upstream emissions per functional unit and facilitates partial internalization of waste within a closed-loop production cycle, forming an example of applied circular economy principles (Bansod et al., 2024a).

4.2 Waste Reclassification and Resource Circularity

In conventional industrial practice, metallic swarf contaminated with petroleum emulsions and biocidal additives is classified as hazardous waste under EU Directive 2008/98/EC and corresponding national legislation (European Union, 2008). This classification imposes costly storage, transport, and disposal requirements, often exceeding the value of the recoverable metal content. The introduction of non-toxic and biodegradable fluids such as glycerol changes this classification at its source. By substantially reducing persistent organic contaminants and eliminating formaldehyde-releasing agents, metal chips generated under glycerol-based machining may qualify as non-hazardous residues suitable for direct metallurgical recycling (Shokrani et al., 2024). This regulatory shift has both environmental and economic implications. From an environmental perspective, this substitution could reduce landfilling of recyclable metals and limit secondary CO_2 and particulate emissions typically associated with waste incineration. Economically, it shifts waste management from a cost center toward a potential revenue stream, provided that residue cleanliness meets the screening-level thresholds as discussed in Section 6.1.

At the systemic level, this transition exemplifies a circular economy mechanism, namely, the gradual conversion of linear waste outflows into regenerative resource loops. It also demonstrates how sustainability can be achieved not only through innovation at the product level but through redefinition of regulatory boundaries that determine when a material ceases to be “waste”. In this connection, application of glycerol could stimulate incremental institutional learning within sustainability governance, thus illustrating how modest process substitutions may yield measurable systemic effects subsequent to a long duration. Since this review did not perform a comparative LCA/TEA, environmental conclusions were treated as conditional and interpreted using screening-level indicators rather than pooled effect estimates. Table 1 consolidates the quantitative anchors and minimum evidentiary requirements used in this review to judge when claims of environmental impact for glycerol-based MWFs are plausibly supported in real shop conditions, particularly regarding biodegradability, wastewater burden, and the feasibility of maintaining metal residues sufficiently “clean” for circular handling.

4.3 Improvements of Occupational Health and Safety

The occupational dimension of sustainability remains comparatively underrepresented in industrial innovation research, despite being a core pillar of social sustainability. Conventional MWFs release aerosols that can contain polycyclic aromatic hydrocarbons (Hopf et al., 2019), chlorinated paraffins (Cherrie & Semple, 2010), and microbial degradation products (Elansky et al., 2022), i.e., substances associated with respiratory irritation and dermatological disorders. Numerous epidemiological studies have reported correlations between prolonged exposure to specific MWF additives and elevated health risks (Latinović & Marjanović, 2021). More specifically, studies have documented increased incidence of respiratory conditions (Park, 2019; Nett et al., 2021), potentially carcinogenic risks (Costello et al., 2020; Park, 2018), and chronic inflammatory responses among machine operators (Moradpour et al., 2025; Zhou et al., 2024). Replacing these fluids with glycerol-based formulations could substantially mitigate such risks, according to laboratory and pilot-scale evaluations. Non-toxic and hypoallergenic characteristic of glycerol, demonstrated through its long-standing use in food, pharmaceutical, and cosmetic sectors, suggest that dermal contact and inhalation present a low hazard under standard workplace conditions (Becker et al., 2019). In practice, such substitution is expected to result in fewer occupational incidents, reduced medical surveillance needs, and improved indicators of workers' well-being, although long-term field data remain limited. From a corporate sustainability perspective, these outcomes can strengthen social license to operate and contribute to long-term human capital retention. Moreover, the observed reduction in volatile organic compound (VOC) emissions and the absence of formaldehyde donors are consistent with the progressively stricter occupational exposure limits adopted across the EU and OECD member states (Baguley et al., 2025; Cammalleri et al., 2022; Ghaffari Jabbari et al., 2025).

Consequently, the environmental and occupational health advantages of glycerol are mutually reinforcing: by addressing toxicity at the material level, glycerol-based fluids simultaneously support regulatory compliance across the domains of environmental and workplace safety.

Table 1. Thresholds of screening-level evidence for environmental-impact claims of glycerol-based metalworking fluids (MWFs)

Environmental Domain	Quantitative Indicator(s) Used in this Review at the Screening Level	Claimed/Plausible Direction vs. Mineral-Oil Baseline	Minimum Evidence Required to Support the Claim (Context of Application)
Biodegradability & persistence	Demonstrated biodegradability under aerobic/anaerobic conditions (reported in the literature as a key glycerol advantage)	Lower persistence and lower long-term environmental loading are plausible	Report biodegradability evidence for the formulated fluid (base + additives), preferably via standardized criteria where available (e.g., "ready biodegradability" framing used in policy discussions)
Wastewater organic load & toxicity	COD reduction in shop-relevant wastewater streams of ~30–60% (controlled conditions); reduced effluent toxicity indices (controlled conditions)	Potential reduction in effluent burden vs. petroleum emulsions	Measure COD/biochemical oxygen demand (BOD) (and toxicity where applicable) in operational effluent; document capture/treatment compatibility; avoid extrapolating from laboratory-only conditions
Waste reclassification & resource circularity	Regulatory classification leverage: Petroleum-emulsion-contaminated swarf is commonly treated as hazardous under EU waste governance; glycerol-based fluids are argued to change contamination at source	Improved circular handling is plausible if residues meet classification thresholds	Verify classification criteria in the relevant jurisdiction; demonstrate swarf cleanliness via measured contamination/chemical profile consistent with non-hazardous handling requirements
Air emissions from thermal stress (environmental + occupational health and safety (OHS) interface)	Thermal dehydration risk becomes material above ~280–300 °C (acrolein formation discussion); screening uses ppm-scale anchors elsewhere in the manuscript	Potentially new emission pathway in high-thermal regimes	Provide the process-window envelope (materials and cutting regime) and show that thermal severity is bounded; where high thermal loads are plausible, report monitoring/verification consistent with the risk framing of the manuscript

Note: Screening indicators were used as interpretive guardrails rather than universal performance guarantees; several benefits were explicitly conditional on operating regime and end-of-life handling.

4.4 Socio-Economic Implications and Industrial Symbiosis

The sustainability potential of glycerol extends beyond its direct environmental and health effects to include cross-sectoral economic linkages and value-chain interactions. Its use in metalworking could foster industrial symbiosis between the renewable energy sector, where biodiesel production generates surplus glycerol, and the manufacturing sector, which consumes large volumes of lubricants and coolants. This linkage exemplifies the resource-efficiency logic of industrial ecology, in which the by-product of one sector becomes another's feedstock, thereby reducing the demand of primary material (Frosch & Gallopoulos, 1989).

The economic implications are twofold, involving both market stabilization effects and operational efficiency gains. First, redirecting surplus glycerol into industrial use could help moderate market volatility, historically fluctuating between €80 and €600/t, and reduce the disposal burden for biodiesel producers (Business Analytiq, 2025; Ciriminna et al., 2014). Second, manufacturers adopting bio-based fluids may achieve measurable cost savings in waste management, ranging from 10% to 30% in pilot implementations, and enhanced sustainability performance, which increasingly shapes access to green financing and public procurement opportunities (Kumar et al., 2023; OECD, 2024; Ye & Dela, 2023).

At a broader policy level, such cross-sectoral integration aligns with national bio-economy strategies and exemplifies how renewable resource valorization could contribute to industrial competitiveness while advancing sustainability objectives (Bansod et al., 2025; Tomatis et al., 2024). The glycerol case thus illustrates an ongoing shift from substitution at the product level toward systemic resource governance, in which environmental, social, and economic dimensions of sustainability are addressed concurrently and interdependently (Geissdoerfer et al., 2020; Kirchherr et al., 2018).

5. Systemic Limitations and Trade-Offs

While Section 4 emphasizes the environmental and occupational benefits of glycerol-based MWFs, this section reinterprets those findings through the lens of sustainability trade-offs. It asked under which operational and institutional conditions the apparent advantages of glycerol were preserved, eroded or reversed, and how technical limitations could generate rebound effects that partly offset the gains identified earlier.

5.1 Thermal Instability and Process Constraints

Despite its environmental advantages, glycerol exhibits several technical limitations that restrict broad applicability in industrial metalworking operations. The most consequential is thermal instability at elevated temperatures. Under high cutting speeds or heavy tool loads, localized temperatures at the tool–workpiece interface can reach or exceed 200–300 °C (Kreivaitis et al., 2023; Ratnawati et al., 2022; Tamayo et al., 2022). Under these conditions, glycerol undergoes viscosity reduction and loss of lubricity and, at temperatures typically above ~280 °C, partial chemical dehydration. These transformations weaken heat removal and could precipitate lubrication breakdown, hence accelerating tool wear and degrading surface finish (Kreivaitis et al., 2023; Li et al., 2025; Ratnawati et al., 2022). Importantly, performance constraints could emerge even below decomposition thresholds because the rheology of glycerol is strongly temperature-dependent: published property data indicate that neat glycerol viscosity decreases from 1412 mPa·s at 20 °C, 612 mPa·s at 30 °C to 14.8 mPa·s at 100 °C (Cheng, 2008; Segur & Oberstar, 1951). This magnitude of thinning helps explain why thermal stress could alter film formation and mist generation. It also motivates explicit reporting and control of both bulk-fluid temperature and overheating of local interface in any performance or sustainability claims.

This thermally induced instability narrows the effective application window of glycerol to low-to-moderate temperature operations, typically involving high-speed steel (HSS) tools or low-alloy steels (Kreivaitis et al., 2023; Tamayo et al., 2022). Accordingly, glycerol-based fluids have shown satisfactory performance in finishing, drilling, and tapping (Leiden et al., 2023; Momeni et al., 2024; Ribeiro Filho et al., 2020; Wichmann et al., 2013; Winter et al., 2012), whereas suitability for high-speed carbide machining or heavy-duty milling, where flash temperatures can surpass 400 °C, remains limited (Espinoza-Torres et al., 2023; Eto et al., 2024; Shi et al., 2014; Tamayo et al., 2022).

From a sustainability transition perspective, the net balance is therefore explicitly conditional. A substitution that lowers toxicity and enables waste reclassification but simultaneously shortens tool life or fluid service intervals, shifts part of the burden upstream into tool manufacture, fluid production, and energy use. As an illustrative scenario, a substitution that introduces performance penalties, specifically a reduction in tool life (~10–20%) or an increase in fluid replacement frequency (~2×) relative to a mineral-oil baseline, would generate rebound effects that erode the gains from reduced hazardous waste. These critical sensitivity thresholds are defined in Section 5.5 to bound the validity of the sustainability claims.

5.2 Formation of Acrolein and Secondary Emission Risks

A more critical concern pertains to the potential formation of acrolein, a toxic and volatile aldehyde generated through glycerol dehydration under elevated temperatures (Liu et al., 2025; Zhang et al., 2021). Acrolein is a potent irritant and a well-documented respiratory hazard (EPA, 2003; National Research Council US Committee on Acute Exposure Guideline Levels, 2010). To ground this risk discussion quantitatively, acute exposure guideline levels (AEGLs) provide ppm anchors across realistic time windows: AEGL-1 is 0.030 ppm (10 min–8 h); AEGL-2 is 0.44 ppm (10 min), 0.18 ppm (30 min), and 0.10 ppm (1–8 h); and AEGL-3 is 6.2 ppm (10 min), 2.5 ppm (30 min), 1.4 ppm (1 h), 0.48 ppm (4 h), and 0.27 ppm (8 h) (EPA, 2014). These values do not imply that such concentrations occur in machining by default; rather, they define what must be ruled out via temperature control, enclosure/local exhaust ventilation (LEV), and monitoring in thermally demanding operations. Although experimental studies suggested that measurable acrolein formation occurred primarily above 280–300 °C, transient thermal spikes at the cutting edge might occasionally exceed this threshold (Akbari et al., 2018; Cichosz et al., 2023). As a trace-level point of reference from a non-analogous thermal context, controlled crude-glycerol combustion experiments have reported exhaust acrolein on the order of ~15 ppbv (Steinmetz et al., 2013). In machining-relevant conditions, Winter et al. (2012) repeatedly sampled air at and inside an encased grinding machine operated under worst-case conditions (deaeration shut down; glycerol shares up to 70%) using dinitrophenylhydrazine (DNPH) cartridges followed by high-performance liquid chromatography (HPLC). They reported no detectable volatile carbonyls (aldehydes/ketones) above method detection limits across glycerol-based variants, thus suggesting that, in at least some controlled grinding regimes, carbonyl emissions remained below quantifiable levels. This phenomenon illustrates a sustainability paradox: even a biogenic fluid could emit harmful compounds when subject to extreme thermo-mechanical stress. Consequently, risk mitigation cannot rely solely on general workshop ventilation. Effective control requires point-of-source LEV to capture emissions directly at the cutting zone, combined with real-time aldehyde monitoring in any operation where interface temperatures risk crossing the dehydration onset. These engineering controls are necessary to ensure compliance with the AEGL thresholds. They also impose penalties on operational energy and capital costs, thus complicating the assumption of simplicity that initially made glycerol attractive.

The net sustainability profile is therefore conditional: it depends on whether the energy burden of abatement is outweighed by the substantial reduction in biocide and mineral-oil exposure. This underscores that industrial sustainability transitions frequently entail secondary risks requiring anticipatory governance (Muiderman et al., 2022). Policy frameworks, therefore, should couple the promotion of bio-based fluids with mandatory exposure monitoring, so as to ensure that the transition to renewable fluids does not merely displace risks from the effluent stream to the worker's breathing zone.

5.3 Feedstock Variability and Challenges to the Supply Chain

Industrially available glycerol exhibits substantial variability in purity and composition, primarily determined by sources of feedstock, processing method, and purification level (Armylisas et al., 2023; Attarbachi et al., 2024; Husna et al., 2024; Tomatis et al., 2024). Crude glycerol obtained as a by-product of biodiesel production typically contains 3.5–45 wt% impurities (Table 2, Figure 4), including residual methanol, soaps, salts, and free fatty acids, reflecting the variability of feedstock quality and catalyst recovery processes (Armylisas et al., 2023; Bansod et al., 2024a; Chilakamarry et al., 2021; Yang et al., 2012). Since technical or industrial-grade glycerol is not harmonized across sectors, Table 2 does not treat it as an official grade. Instead, it pairs reported impurity ranges with a screening-level "spec limit (proposed)" column intended for glycerol streams considered for MWF formulation and use. These proposed limits are not a formal standard, but operational guardrails derived by triangulating (i) available grade specifications where they exist (e.g., refined glycerin TECH grade requirements in IS 1796:2023) (Bureau of Indian Standards, 2023) and (ii) biodiesel-process crude-glycerin bounding maxima and definitions used in sectoral descriptions (e.g., methanol and Matter Organic Non-Glycerol (MONG) ceilings and the definition of MONG) (European Union, 2013), together with machining-relevant constraints (corrosion sensitivity, foaming/deposits, emissions, and biological robustness). In principle, even low-purity crude glycerol may be workable in narrowly defined conditions, but such use should be treated as a controlled exception that requires explicit impurity reporting and validation rather than assumed equivalence to higher-grade feedstock.

The presence and proportion of these impurities significantly affect viscosity, tendency of corrosion, and long-term chemical stability (Attarbachi et al., 2023; Palcut et al., 2023; Zhang & Wu, 2015). Although pharmaceutical-grade glycerol offers superior consistency and purity (>99.5%), its high production cost, often five to seven times that of crude grades, limits its feasibility for large-scale industrial deployment (Bansod et al., 2025; Moklis et al., 2023; Pandit et al., 2023). This dichotomy constitutes a sustainability dilemma: purification processes increase energy and resource consumption, thus eroding part of the environmental advantage of bio-based fluids whereas unrefined glycerol introduces operational, corrosion, and quality-control risks. Achieving a balance between these extremes necessitates the establishment of standardized specifications for industrial-grade glycerol, i.e., an institutional and regulatory task rather than a purely technical one. In the absence of such standards, batch-to-batch variability is likely to continue hindering scalability, discouraging industrial investment, and constraining adoption beyond pilot implementation.

Stability of the supply chain represents an equally critical determinant of the industrial viability of glycerol. As a by-product, the availability of glycerol is directly linked to biodiesel production volumes and to policy incentives for renewable fuels (US Department of Energy, n.d.; Awogbemi & Desai, 2025; Latinović et al., 2020; Liu et al., 2022; Moklis et al., 2023; Wan Osman et al., 2024; Wang et al., 2024). Fluctuations in the prices of biodiesel feedstock and inconsistent glycerol output volumes can disrupt the planning of long-term procurement and pricing stability for downstream manufacturers. A systemic response may therefore involve formal contractual integration between biodiesel producers and manufacturing firms, institutionalized through industrial symbiosis agreements, shared logistics platforms, or regional circular economy clusters.

Table 2. Typical composition, ranges of impurity, and proposed specification limits for crude glycerol in applications of metalworking fluids (MWFs)

Component (Reference)	Range (wt%)	Notes	Implications for MWF Performance[1]	Spec Limit (Proposed)[2]
Glycerol (Hansen et al., 2009; Sakamoto et al., 2021; Wang et al., 2024)	45–96.5	Main component	Governs rheology and boundary lubricity. High content enhances film strength and load capacity but increases pumping demand and lowers cooling efficiency. While hygroscopicity aids wetting, strict concentration control is essential to mitigate water sensitivity and maintain process stability.	≥90% (≥95% preferred when stability/corrosion sensitivity is high)
Methanol (Hansen et al., 2009; Uprety et al., 2017; Wang et al., 2024)	0–14	Residual from transesterification	High volatility lowers flash point and increases flammability. Reduces viscosity and surface tension, aiding wetting but compromising boundary lubrication. Increases inhalation and dermal toxicity risks, attacks elastomeric seals, and contradicts low-toxicity goals, necessitating pre-treatment stripping.	≤0.5 (target ≤0.1 for low-volatility/low-emission handling)
Soap (Maneerung et al., 2016; Mize et al., 2013; Sakamoto et al., 2021; Wang et al., 2024)	0.04–25	Formed by reaction of free fatty acids and catalysts	Acts as an in-situ surfactant. Moderate levels enhance detergency and chip cleaning. High concentrations increase alkalinity and foaming risk. Excess soap forms deposits, disrupts boundary lubrication films, aggravates skin irritation, and hinders filtration efficiency.	≤1.0 (target ≤0.5 to reduce foaming/deposits/alkalinity swings)
Water (Dobrowolski et al., 2016; Hansen et al., 2009; Wang et al., 2024)	0–12	Moisture present from production and washing	Reduces viscosity, enhancing flow and heat transfer for effective cooling and chip evacuation. Controlled dilution tunes the cooling-lubrication balance. Excessive levels compromise boundary-film strength, particularly with dissolved salts, and accelerate corrosion and surface staining.	≤5.0 in concentrate (final formulation is application-specific)
Inorganic Salts/Ash (Dianningrum et al., 2014; Hansen et al., 2009; Wang et al., 2024)	0–30	Alkaline catalyst and neutralization products	Increases ionic strength and conductivity, accelerating uniform and localized corrosion. Precipitates form hard deposits on heat exchangers and filters, reducing thermal efficiency and increasing maintenance downtime.	≤0.5 (target ≤0.1 where corrosion risk is dominant)
Free Fatty Acids (Attarbachi et al., 2024; Kumar et al., 2019)	2–7	Unreacted or released in process	Polar molecules absorb to surfaces, enhancing boundary lubrication. However, the susceptibility to oxidation causes rancidity and viscosity drift. Excess levels promote foaming and instability, damage elastomers, and hinder corrosion control by lowering pH and competing with inhibitors.	≤2.0 unless intentionally used as boundary
MONG[3] (Dianningrum et al., 2014; Hansen et al., 2009; Wang et al., 2024)	1–30	Matter organic non-glycerol	Heterogeneous organic pool (esters and oligomers) causes rheological and aging uncertainty. While some fractions aid lubricity, others promote varnish, sludge, and fouling. Elevated levels act as microbial nutrients, in order to	≤5.0 (target ≤2.0 for stability/biolo-gical robustness)

		accelerate degradation, reduce performance reproducibility, and mandate strict purification or specification limits.	
Total impurities	3.5–55	High levels narrow the safe operating window, amplifying variability in viscosity, corrosion behavior, and thermal stability. Lower contents permit selective functional benefits, whereas higher loads necessitate pre-treatment to prevent equipment wear and regulatory failure. Serves as the primary parameter for feedstock qualification.	≤10 (target ≤5 for consistent industrial operation)

Note: [1] The 'Implications for MWF Performance' column summarized the authors' analytical inferences for glycerol-based MWFs, based on the literature analyzed in Section 3–6, rather than reporting direct empirical findings for each framework. [2] Denotes screening-level acceptance targets for biodiesel-derived glycerol intended for formulation of MWF concentrate; it is not a consensus standard and should not be read as a regulatory requirement, or a universally defined "industrial-grade" category. [3] MONG is defined as: 100 – [glycerol content (%) + water content (%) + ash content (%)].

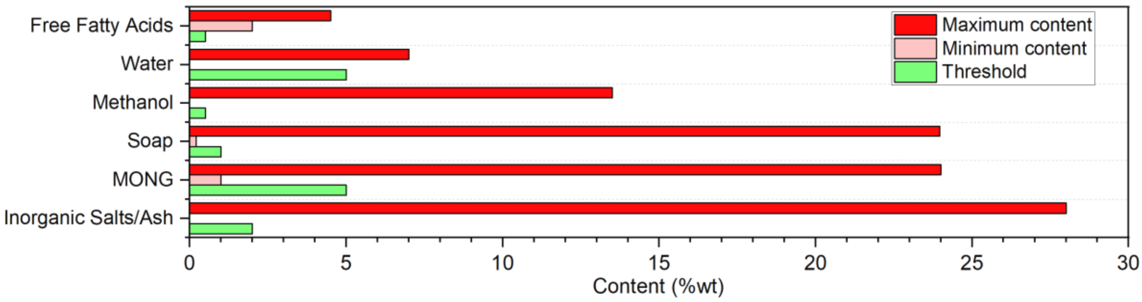

Figure 4. Minimum, maximum, and threshold contents of major impurities in crude glycerol, based on the ranges reported in Table 2

5.4 Compatibility with Existing Industrial Infrastructure

Another structural barrier concerns the legacy infrastructure embedded within existing manufacturing facilities. Machine tools, pumps, filtration systems, and coolant re-circulation loops were originally designed for low-viscosity petroleum-based emulsions (KCL, n.d.; MSC Filtration, n.d.; Wanner Engineering, n.d.). Higher kinematic viscosity of glycerol, typically three to five times that of conventional emulsions (Okhiria et al., 2024), and its hygroscopic nature (Ault et al., 2023) may cause operational incompatibilities, clogging, or corrosion if existing systems are not adequately adapted. Retrofitting or re-configuring existing systems entails significant upfront investment and temporary operational downtime, which many firms, particularly small and medium-sized enterprises (SMEs), may consider economically prohibitive. This highlights the importance of transition-support mechanisms, such as targeted tax incentives, public–private demonstration programs, and standardized technical guidelines, in lowering adoption barriers and diffusing learning across firms. In the absence of such enabling conditions, technological potential is unlikely to be translated into practical deployment. Sustainability transitions at the industrial level depend not only on technological innovation but also on institutional capacity to reconfigure the socio-technical infrastructures that underpin production systems.

5.5 Trade-Offs and Limits of Substitution

The scenarios outlined in Section 5.1 to 5.4 show that the technical constraints, impurity profiles, emission risks and infrastructure lock-ins of glycerol can be translated into concrete sustainability trade-offs. The cumulative evidence indicates a nuanced reality: glycerol represents not a universal substitute for conventional MWFs but a selective and context-dependent alternative. Its sustainability advantages such as biodegradability, low toxicity, and potential for waste reclassification, remain substantial but are contingent upon specific operational conditions and management strategies. Beyond certain thermal thresholds, these advantages can diminish or invert, thus introducing secondary environmental or economic costs.

From a theoretical perspective, such outcomes exemplify the dynamics of trade-off and rebound effects inherent in sustainability transitions (Geels et al., 2023; Köhler et al., 2019). Innovations frequently shift rather than eliminate impacts, thus redistributing environmental burdens across distinct stages of industrial production and use. The key challenge lies not in pursuing flawless material substitutes but in developing adaptive governance frameworks that minimize systemic risks, optimize net sustainability gains, and foster continuous cross-sectoral learning through collaborative partnerships, thereby operationalizing SDG 17 as an enabling dimension of industrial sustainability transitions.

Ultimately, the limitations of glycerol illustrate that sustainable manufacturing is a process of managed balance rather than a pursuit of technological perfection. Recognizing and governing such trade-offs is essential for translating laboratory success into systemic industrial resilience and policy-relevant sustainability outcomes. For operational clarity, Table 3 consolidates the screening-level quantitative anchors and guardrails that define when these trade-offs become material in practice.

Table 3. Screening-level quantitative anchors and operational guardrails used to interpret benefit–risk trade-offs

Risk/Trade-Off	Quantitative Anchor (Screening-Level)	Use in This Review	Operational Guardrail/Control Lever
Thermal severity and dehydration regime at the tool–workpiece interface	Interface temperatures can enter ~200–300 °C under high cutting speeds/heavy loads; measurable glycerol dehydration to acrolein is reported primarily above ~280 °C	Delineates the regime in which thermal degradation and secondary-emission risks become plausible and must be treated as process-relevant constraints.	Risk is typically bounded by defining a validated process window (duty level, cutting parameters, and tooling) that limits sustained overheating, combined with bulk-fluid temperature/heat-removal management; in thermally severe cases, engineering controls (enclosure/local exhaust ventilation) and monitoring provide verification.
Viscosity collapse under thermal stress	Neat glycerol viscosity: 1412 mPa·s at 20 °C, 612 mPa·s at 30 °C to 14.8 mPa·s at 100 °C	Connects thermal stress to film-formation conditions, fluid handling behavior, and the plausibility of increased aerosol generation; supports the requirement to report thermal conditions alongside rheology-relevant metrics.	Operational control relies on explicit reporting of bulk temperature and viscosity/rheology (or validated surrogate), coupled with heat-management design; where applicable, formulation tuning (e.g., controlled water content/additives) is treated as a managed variable rather than an uncontrolled impurity.
Acrolein exposure interpretation (ppm scale)	AEGL benchmarks for acrolein: AEGL-1 = 0.030 ppm (10 min–8 h); AEGL-2 ≈ 0.10 ppm (1–8 h); AEGL-3 = 0.27 ppm (8 h)	Provides a ppm-scale reference for interpreting monitoring data and framing “what must be ruled out” when thermal severity suggests dehydration risk.	Controls typically combine source containment and ventilation with exposure verification (monitoring and comparison to applicable occupational guidance); exceedance-level signals are treated as grounds for process-window restriction or redesign.
Feedstock variability and specification control	Proposed metalworking fluid (MWF)-grade procurement/specification limits are summarized in Table 1	Translates upstream variability into procurement and quality-control conditions, linking impurity control to corrosion risk, foaming/deposits, thermal stability, and biological robustness.	Governance is implemented through purchasing specifications, certificates of analysis, and/or lot testing, and where pretreatment steps are required (e.g., neutralization, filtration, and phase separation), with batch-to-batch variability tracked against in-process performance outcomes.
Rebound effects (offsetting of system-level gains)	Screening sensitivity case: tool life -10–20% and fluid replacement frequency ~2 × relative to a mineral-oil baseline in thermally demanding operations	Defines an illustrative magnitude of performance penalties that could plausibly erode net environmental/economic gains, thus motivating explicit bounding of claims to validated operating regimes.	Control consists of measuring tool life and service intervals within the target process window, and restricting benefit claims to conditions where these rebound terms are demonstrably bounded; optimization focuses on parameter selection and formulation stability within the defined regime.

6. Industrial Feasibility and Governance Implications

6.1 Economic Rationale and Market Dynamics

The industrial feasibility of glycerol-based MWFs cannot be meaningfully assessed solely through technical performance or environmental indicators. Sustainable adoption depends equally on economic rationality, market integration, and the capacity to internalize externalities across value chain (Alamandi, 2025; Chatterjee et al., 2023; Tang, 2024; Thun et al., 2024). From a cost-structure perspective, the transition from petroleum-based emulsions to glycerol-based formulations generates both potential saving and new categories of expenditure. Table 4 delineates the screening-level evidence thresholds required to validate these claims, so as to categorize the economic variables into waste management, feedstock volatility, process adaptation, and externality internalization.

On the saving side, the reclassification of metallic residues from hazardous to non-hazardous waste significantly alters the economic balance. As indicated in the “Waste-management swing” domain of Table 4, this reclassification effectively converts a disposal liability into a revenue source via scrap trading, provided residue cleanliness meets buyers' acceptance criteria. Although precise data on the generation of global steel swarf remain scarce, machining of steel components produces substantial quantities of ferrous and non-ferrous residues (Salihoğlu et al., 2018). Earlier estimates placed the generation of global steel swarf between 2.3 and 5.8 million tonnes (Chang et al., 2006), with more recent analyses proposed that grinding residues alone might account for 10–12 million tonnes worldwide (Ottink et al., 2022). While precise global statistics on machining residues remain opaque, even conservative extrapolations suggest that valorizing around 10 million tonnes of metal swarf annually could yield economic benefits in the range of several hundred million euros, particularly as scrap steel in Europe trades near €220 per tonne (Metaloop, n.d.).

Table 4. Screening-level evidence thresholds for cost saving and economic-plausibility claims of glycerol-based metalworking fluids (MWFs)

Cost-Saving Domain	Screening-Level Quantitative Indicator(s)	Claimed/Plausible Direction vs. Mineral-Oil Baseline	Minimum Evidence Needed to Support the Claim
Waste-management "swing" (disposal vs. recovery)	Hazardous disposal fees: €100–700/t (Inspire Waste Management, 2021; Interreg Europe, n.d.); scrap revenue: €150–300/t (Schrott24, n.d.; Metaloop, n.d.; ScrapMonster, n.d.); implied screening swing ≈ €250–1000/t (computed from cited ranges)	Net waste cost may decrease if swarf can be reclassified and placed on the scrap market	Local classification pathway and acceptance criteria documented; fee schedules and scrap-price baselines established; residue cleanliness demonstrated at a level consistent with reclassification and buyer acceptance
Feedstock market volatility & procurement risk	Glycerol price volatility cited as €80–600/t (historical); waste-management saving of 10–30% reported in selected pilots (context-dependent)	Economic plausibility may improve, but can be fragile under price/quality swings and contract terms	Procurement basis specified (grade, certificate-of-analysis requirements, and contract term); sensitivity of operating costs to glycerol price and quality variability quantified for the target setting
Process adaptation & retrofit costs	Cost categories highlighted: coolant-system retrofit, process adaptation, and maintaining stability under elevated temperatures (site-specific; front-loaded)	Added capital expenditures (CAPEX)/operating expenses (OPEX) can offset early stage savings	One-time vs. recurring costs itemized (hardware, filtration, handling, and downtime); compatibility constraints documented (seals, storage, and chip handling)
Rebound costs from performance penalties	Screening sensitivity case: tool life -10–20% and fluid replacement frequency ~2× in thermally demanding operations	If present, rebound costs can erase part of the economic case via higher tool and fluid throughput	Tool life and service interval reported in the relevant process window; fluid make-up, disposal volumes, and tooling consumption quantified per unit output
Internalization of externalities (boundary condition for "viable")	Viability may improve when avoided waste costs and potential carbon-pricing/credit effects are internalized (no universal numeric claim)	Can shift break-even conditions in favor of glycerol-based fluids	Accounting boundary stated (whether carbon pricing/credits are applied); assumptions documented and tied to a jurisdictional basis for any credited saving

However, these potential savings are offset by new expenditures related to process adaptation, retrofitting of coolant systems, and maintaining fluid stability under elevated temperatures. These costs are typically front-loaded but can be mitigated through economies of scale and collaboration across industrial clusters. When assessed through a life-cycle cost lens, glycerol-based fluids may become financially viable once avoided waste-management costs and potential carbon credits from reduced emissions are internalized. Concurrently, establishing a high-value outlet for glycerol offers a theoretical pathway to utilize biodiesel-derived surpluses. While the extent of any market stabilization depends heavily on global adoption rates, such valorization strategies could provide a mechanism to absorb local oversupply, thereby suggesting a potential economic symbiosis between the renewable energy and manufacturing sectors (Pandit et al., 2023). In this way, the adoption of glycerol in metalworking could foster economic symbiosis between the renewable energy and manufacturing sectors, hence advancing circularity, resilience, and alignment with SDG 17 on cross-sectoral partnerships.

6.2 Policy and Regulatory Frameworks

Governance structures play a decisive role in determining whether such forms of industrial symbiosis remain isolated niche innovations or evolve into broader transformative pathways. Currently, the deployment of glycerol-based fluids remains constrained by the absence of explicit recognition within environmental policy instruments and industrial standards (Attarbachi et al., 2023). Regulatory frameworks governing lubricants, waste management, and occupational safety have historically been tailored to mineral-oil formulations, thereby unintentionally marginalizing bio-based alternatives (European Union, 2018; Vidal et al., 2018). To move beyond this structural bias, generic support for "bio-based products" is not sufficient. Instead, a set of targeted and actionable measures is required at different governance levels. Incentive-based regulation could be made explicitly contingent on the hazard profile and end-of-life performance of MWFs. At national level, modulated waste charges or environmental fees (Malinauskaite et al., 2017) could grant reduced tariffs for glycerol-based fluids that (i) achieve ready biodegradability under OECD 301 tests (OECD, 1992), (ii) comply with aquatic toxicity thresholds aligned with EU Ecolabel criteria (European Union, 2018), and (iii) can be classified as non-hazardous waste streams under the List of Waste. In parallel, time-limited investment subsidies or accelerated depreciation allowances could support small and medium enterprises (SMEs) in retrofitting central coolant systems, thus installing filtration units compatible with aqueous fluids and adapting cutting parameters to glycerol-based formulations. This shifts incentives from generic "green subsidies" to a clearly defined class of fluids that deliver lower toxicity and improved recyclability in practice. Moreover, eco-labelling and certification schemes could be tightened to explicitly include glycerol-based MWFs as a recognized product group. At the EU level, the Ecolabel Decision for lubricants could be revised to introduce a dedicated subcategory for MWFs, with criteria that (i) recognize glycerol and its low-toxicity derivatives as "preferred base fluids", (ii) restrict the use of formaldehyde releasers, isothiazolinones, and other high-concern additives, and (iii) require tribological performance to be demonstrated on representative steels and machining regimes. At the same time, relevant International Organization for Standardization (ISO) and European Committee for Standardization (CEN) standards for MWF performance (e.g., within the ISO 6743 lubricant taxonomy) could incorporate reference test methods for glycerol-based formulations. The practical effect would be to provide formulators and users with a clear and standardized route to demonstrate compliance, instead of relying on case-by-case interpretation of oil-oriented standards.

Green public procurement could be used to create a lead market for glycerol-based fluids in applications where their technical envelope is well matched to operational conditions (Krieger & Zipperer, 2022). Public bodies that outsource machining, maintenance or infrastructural works could require, in tenders above a defined budget threshold, either (i) the use of MWFs meeting specified eco-label or equivalent criteria, or (ii) a documented justification for non-use. Award criteria could allocate a fixed share of points (e.g., 10–15%) to demonstrable use of low-toxicity and recyclable fluids and to documented schemes for recovering and treating spent glycerol-based coolants via industrial symbiosis (e.g., anaerobic digestion and recovery in other industrial processes). This would turn the public sector into an early adopter that lowers risks of the technology for users.

Harmonization of waste policy and permitting practice is required to convert the potential reclassification of spent fluids into a predictable regulatory outcome. At the EU level, guidance on the application of the List of Waste could clarify under which compositional and toxicity criteria spent glycerol-water MWFs may be coded as non-hazardous (e.g., under 12 01 05) when segregated and treated separately from mineral-oil emulsions (Your Dsposal, n.d.). National environmental authorities could issue standardized permits or "general binding rules" for the recovery of such streams in industrial symbiosis schemes, in order to specify monitoring requirements for metals, organic contaminants, and odor. This would reduce the current dependence on case-by-case administrative discretion, which is particularly burdensome for SMEs and discourages experimentation with alternative fluids.

Finally, occupational safety and process-integrity regulations must be updated in parallel to ensure that the thermal and degradation characteristics of glycerol-based fluids are adequately governed. This could include (i) binding exposure limits and monitoring requirements for degradation products such as acrolein, (ii) explicit guidance in occupational hygiene standards on the design and ventilation of systems using aqueous glycerol fluids, and (iii) integration of MWF substitution into mandatory risk assessment procedures in line with the hierarchy of controls. By coupling substitution with robust safety governance, regulators could avoid a "silent" shift of risks from waste and environmental domains into the workplace.

Integrating these measures would gradually transform glycerol adoption from a voluntary niche innovation into a structured component of industrial sustainability policy, aligned with multi-level governance frameworks underpinning SDG 12 and SDG 17. Instead of isolated pilot projects, glycerol-based fluids would be embedded in a coherent policy mix that combines economic incentives, standards, procurement, and waste regulation. In this way, technological substitution is anchored in long-term governance trajectories, while preserving flexibility to adjust criteria as new toxicological and operational evidence emerges.

6.3 Institutional Barriers and Lock-Ins

Despite a clear environmental and economic rationale, transitions of this nature frequently encounter institutional inertia and organizational resistance. Manufacturing systems operate as deeply embedded socio-technical regimes, characterized by entrenched supply chains, safety norms, and maintenance protocols (Moran et al., 2025; Sivonen & Kivimaa, 2025) historically optimized around mineral-oil-based technologies. The lock-in effect, stemming from sunk investments, risk aversion, and regulatory path dependency, tends to suppress the diffusion of sustainable alternatives even when empirical evidence demonstrated their technical or environmental superiority (Eitan & Hekkert, 2023; Geels, 2025; Klitkou et al., 2015). This inertia is further reinforced by fragmented institutional responsibilities across agencies governing energy, environment, and industrial policy. Bio-based lubricants currently occupy a regulatory blind spot, positioned between renewable resource policy and chemical or hazardous waste management, thereby lacking explicit recognition within most frameworks of environmental and lubricant standards (Cecilia et al., 2020; European Union, 2018). Overcoming these barriers requires inter-ministerial coordination and cross-sectoral dialogue platforms that prevent sustainability innovations from being constrained within bureaucratic silos and fragmented governance structures.

Furthermore, knowledge asymmetries within firms limit the perceived reliability and operational trust in bio-based fluids. Operators and engineers are often unfamiliar with the handling characteristics of biolubricants, which can lead to exaggerated perceptions of technical and safety risks (Potera, 2009). Addressing this gap requires capacity building, demonstration projects, and the integration of bio-based technologies into technical and vocational education curricula (Bossink, 2025; Hasanefendic et al., 2025; Zhang et al., 2023). In essence, successful diffusion depends as much on social learning and organizational adaptation as on technical compatibility, reflecting the collaborative partnerships envisioned under SDG 17.

6.4 Multi-Level Governance for Industrial Transition

The complexity of the sustainability transition necessitates a multi-level governance approach, in which local, national, and international institutions interact to enable and coordinate systemic change. At the micro level, firms require targeted incentives and technical guidance to make process substitution economically viable, mitigate uncertainty, and overcome organizational and financial barriers to adoption (Dhami & Zeppini, 2025). At the meso level, industrial clusters and professional associations can act as intermediaries by coordinating shared infrastructure, supporting pilot facilities, and promoting inter-firm learning and knowledge exchange. At the macro level, supranational actors, such as the European Union and the OECD, could harmonize standards, align subsidy schemes, and steer research funding toward circular economy objectives, thereby embedding bio-based technologies within broader policy frameworks for sustainable industry and innovation (European Commission, n.d.; OECD, 2025).

Such governance layering could create vertical coherence, whereby localized experimentation is scaled through national frameworks and anchored in global norms, effectively linking bottom-up innovation with top-down institutional alignment (Allen et al., 2023; Jänicke, 2015). Glycerol-based fluids could thus evolve from isolated sustainability experiments into recognized components of integrated industrial sustainability strategies. This trajectory mirrors that of renewable energy transitions, progressing from niche experimentation, through regulatory integration, to eventual market mainstreaming once critical policy and investment thresholds are achieved. To operationalize this vision, an indicative industrial roadmap would be required. Such a roadmap should define clear stages:

(1) Pilot and demonstration phase—Testing glycerol-based fluids under real industrial conditions, with systematic monitoring of emissions, tool life, and waste reclassification outcomes;
(2) Standardization phase—Establishing harmonized norms for glycerol purity, viscosity, and stability, and developing standardized safety data sheets and handling protocols;
(3) Incentivization phase—Deploying fiscal and regulatory mechanisms to promote large-scale substitution across strategically selected industrial sectors (e.g., automotive and precision machining);
(4) Integration phase—Embedding glycerol-based lubrication within national circular economy strategies, aligned with waste valorization and policies of renewable resource utilization.

Each stage requires collaboration among academia, industry, and government agencies, in order to form the triple-helix structure defined by the sustainability transition theory. Such partnerships could ensure continuous feedback among research, regulation, and practice, so as to reduce uncertainty, foster trust, and advance the collaborative spirit embodied in SDG 17.

6.5 Societal and Ethical Dimensions

Ultimately, sustainable industrial transformation should encompass societal acceptance, distributive equity, and ethical responsibility. The transition to bio-based industrial systems is not merely technical but also cultural, challenging long-standing assumptions about productivity, safety, and the very foundations of industrial value creation. By aligning cleaner production with human health protection and waste reduction, glycerol-based MWFs contribute to a broader vision of just sustainability, a paradigm in which ecological integrity and social welfare are not competing objectives but mutually reinforcing priorities consistent with SDGs 9, 12, and 17. This ethical dimension reinforces the rationale for proactive policy intervention and inclusive governance. Ensuring that workers, small manufacturers, and local communities equitably benefit from the transition is essential for its legitimacy, distributive justice, and long-term socio-economic stability. In this regard, the trajectory of glycerol transcends its chemical properties. It becomes a microcosm of the dilemmas and opportunities that define the pursuit of industrial sustainability in the twenty-first century.

7. Conclusions

We have critically examined the potential of glycerol as one of the several enablers of sustainable transformation in the metalworking industry. The analysis suggested that glycerol-based MWFs would not simply replace one lubricant with another, but changed how waste, risk, and responsibility were configured across the system. Cleaner process fluids could, in some cases, support the reclassification of metallic residues from hazardous to non-hazardous streams, reduce workers' exposure to biocides and VOCs, and lower the regulatory and financial burden of waste management. At the same time, the paper underlined that these gains were contingent on real operational limits. Thermal instability, acrolein formation, and feedstock variability restrict the use of glycerol to specific temperature windows and tool–material combinations, and thus rule out simple narratives of universal substitution. Beyond these specific findings, the distinctive contribution of this paper lied in offering a rare transdisciplinary synthesis that connects the tribological, anticorrosive and biostatic behavior of glycerol directly with waste-classification regimes, occupational health risks, and transition-governance frameworks. Rather than treating these as separate literatures, the review integrated them into a single systemic roadmap that spans from tool–material–fluid interactions on the shop floor to policy instruments such as minimum purity standards, ecolabel criteria, waste codes, and green public procurement. In doing so, it clarifies not only where glycerol-based MWFs are technically and environmentally promising, but also which combinations of process adaptation, arrangements of industrial symbiosis, and regulatory reforms are needed for the net sustainability balance to remain positive. Viewed from this wider perspective, the surplus of crude glycerol from biodiesel production ceases to be a disposal problem at the margin of the energy system and becomes a test case for deliberate integration of by-product streams into other industrial metabolisms. Coordinated action across firms, sectoral associations, and public authorities, in line with the partnership logic of SDG 17, is therefore a precondition for any durable transition in which glycerol could contribute to cleaner and sustainable manufacturing practices. This work provides a systemic roadmap for identifying and sequencing those interventions.

Author Contributions

Conceptualization, L.L. and S.M.; methodology, L.L. and V.T.; validation, L.L., S.M., and V.T.; investigation, L.L.; resources, L.L.; data curation, L.L.; writing—original draft preparation, L.L.; writing—review and editing, S.M. and V.T.; visualization, L.L.; supervision, S.M. and V.T. All authors have read and agreed to the published version of the manuscript.

Data Availability

Not applicable.

Conflicts of Interest

The authors declare no conflicts of interest.

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