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The Intellectual and Thematic Landscape of Waste Lubricant Oil Management Research through a Combined Bibliometric Analysis and Systematic Literature Review (SLR)

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ABSTRACT:

This study systematically maps the intellectual and thematic landscape of Waste Lubricant Oil (WLO) management research by combining bibliometric analysis and a Systematic Literature Review (SLR) using the TCCM (Theory-Context-Characteristics-Methodology) framework. The research acknowledges the profound shift in WLO management—from a pollution-control problem to a crucial resource recovery imperative aligned with the circular economy. The bibliometric analysis of 215 unique documents published between 2000 and 2025 reveals a mature and expanding field, with a notable surge in production after 2015 and rising influence from emerging economies like South Africa and China. The field is primarily anchored in two interconnected thematic clusters: tribological performance (for example, rolling oil, friction) and environmental sustainability (for example, recycling, regeneration). The SLR component, synthesizing 59 selected studies, confirms the field's grounding in theories of life-cycle assessment (LCA), industrial symbiosis, and green chemistry. Contextually, the research spans industrial applications (steel, energy) and environmental remediation. Methodologies predominantly include experimental designs for regeneration (solvent extraction, membrane separation) and thermo-chemical conversion (pyrolysis, hydrocracking), increasingly supported by pilot-scale validation and systems-level modelling (LCA, MCDA) for sustainability optimization. The combined approach provides a holistic understanding of WLO management as a critical frontier for advancing cleaner production, energy efficiency, and circular economy practices. In this paper a section has been specifically devoted for policy implications to promote circularity in waste lubricant oil management.

Introduction

The rapid industrial expansion of the past decades has led to a sharp rise in the consumption of lubricants, particularly in energy-intensive sectors such as steel rolling, automotive services, power generation, and heavy machinery. Lubricating oils play a critical role in reducing friction, wear, and energy losses; however, their disposal after use has emerged as a significant environmental and industrial challenge. Waste lubricant oil is classified as hazardous wastes due to their complex composition of heavy metals, polycyclic aromatic hydrocarbons, and other toxic compounds. If mismanaged, these residues pose risks of soil and water contamination, air pollution through incineration, and long-term ecological damage. Consequently, the valorisation of waste oils—through recycling, regeneration, or conversion into alternative fuels—has become a focal point of research and policy debate, aligning with the broader goals of sustainable resource management and circular economy practices.

Globally, the management of waste oils is receiving increasing attention not only for its environmental implications but also for its economic potential. Regeneration processes can recover high-quality base

oils, though thermo-chemical and biological pathways can transform waste streams into valuable energy products or secondary resources. At the same time, advances in tribology, material sciences, and chemical engineering are driving innovations in lubricant design, extending their usability and at the same time ensuring recyclability. The intersection of these diverse research streams reflects a growing recognition that lubricant waste is not merely a disposal problem but a potential resource base capable of contributing to cleaner production, energy efficiency, and climate mitigation strategies.

The contemporary approach to Waste Lubricant Oil (WLO) management marks a profound shift, transforming this historically intractable disposal problem into a crucial resource recovery imperative. For decades, used lubricants were viewed almost exclusively through the lens of pollution control. Classified as hazardous due to their accumulation of heavy metals, polycyclic aromatic hydrocarbons (PAHs), and other degradation products, mismanagement whether through unregulated dumping or simple incineration posed a persistent threat to soil, water, and atmospheric health. The primary objective was merely containment and mitigation of environmental damage.

However, escalating global lubricant consumption, coupled with mounting economic and regulatory pressure, has fuelled a fundamental change in perspective. Researchers and policymakers have increasingly recognized that WLO is not merely a toxic byproduct, but a valuable, high-calorific secondary resource. This recognition is the foundational principle of the circular economy applied to the lubricants sector. The focus has pivoted from costly and environmentally damaging disposal to valorisation, the process of recovering or converting waste materials into products of value.

Technologically, this shift is manifested in two major research areas, firstly by regeneration or re-refining. This pathway aims to recover high-quality base oils, the most valuable component of lubricants. Modern processes, including advanced solvent extraction, hydro-treating, and vacuum distillation, yield regenerated oils that can meet or even exceed the quality of virgin base oils. This directly addresses the resource security issue by reducing reliance on crude oil. The second is the thermo-chemical conversion, where re-refining is not feasible, research explores converting WLO into energy carriers. Processes like catalytic pyrolysis and hydrocracking transform the waste hydrocarbons into usable liquid fuels like diesel-substitutes) or syngas, providing an alternative energy source and displacing fossil fuel consumption.

By framing WLO management as a challenge of maximizing resource recovery rather than minimizing pollution, the research agenda aligns environmental responsibility with economic opportunity. This paradigm shift from a linear waste stream to a circular resource loop underpins the necessity and relevance of investigating the entire intellectual and thematic landscape of WLO research.

Despite the growing volume of research, the field remains fragmented, with studies distributed across multiple disciplines and industrial contexts. On one hand, technical studies explore pyrolysis, solvent extraction, microbial degradation, and membrane separation, often reporting promising laboratory-scale outcomes. On the other hand, systems-based analyses emphasize life cycle assessment, policy frameworks, and economic evaluations, revealing trade-offs between regeneration and energy recovery pathways. Furthermore, the geographical distribution of contributions is uneven, with emerging economies such as China, India, and South Africa increasingly shaping global discourse alongside established research hubs in Europe and North America. This dispersion of focus areas, methods, and contexts highlights the need for a comprehensive synthesis of existing knowledge to clarify theoretical foundations, identify technological trade-offs, and outline policy-relevant pathways for sustainable waste oil management.

To address this need, the present study combines bibliometric analysis and a systematic literature review (SLR) to map the intellectual structure, thematic evolution, and methodological foundations of Waste Lubricant Oil (WLO) research. The bibliometric component analyses publication trends, country-level contributions, citation patterns, and keyword co-occurrence networks, providing insights into the field's growth trajectory and thematic clusters. The systematic literature review, structured through the TCCM (Theory–Context–Characteristics–Methodology) framework, integrates evidence from diverse technological and industrial applications to highlight conceptual underpinnings, contextual drivers, technological pathways, and methodological approaches. Together, these complementary perspectives provide a holistic understanding of the domain, situating WLO not merely as waste management challenge but as critical frontiers for advancing sustainability, industrial efficiency, and circular economy practices.

1. Objectives of the Study

1. Map the intellectual and geographical landscape of waste lubricant oil management research through bibliometric analysis of publication trends, citation networks, and keyword structures.
2. Synthesize the theoretical foundations, industrial contexts, technological pathways, and methodological approaches of existing studies using the TCCM framework.
3. Identify critical research gaps and unresolved challenges, particularly concerning scalability, environmental trade-offs, and methodological standardization.
4. Propose future research directions and policy implications to advance sustainable and economically viable waste lubricant oil management strategies within the framework of circular economy and cleaner production.

2. Data and Methodology

This study adopts a dual methodological approach that integrates bibliometric analysis with a systematic literature review in order to provide both a macro-level mapping of the field and a micro-level synthesis of thematically relevant research.

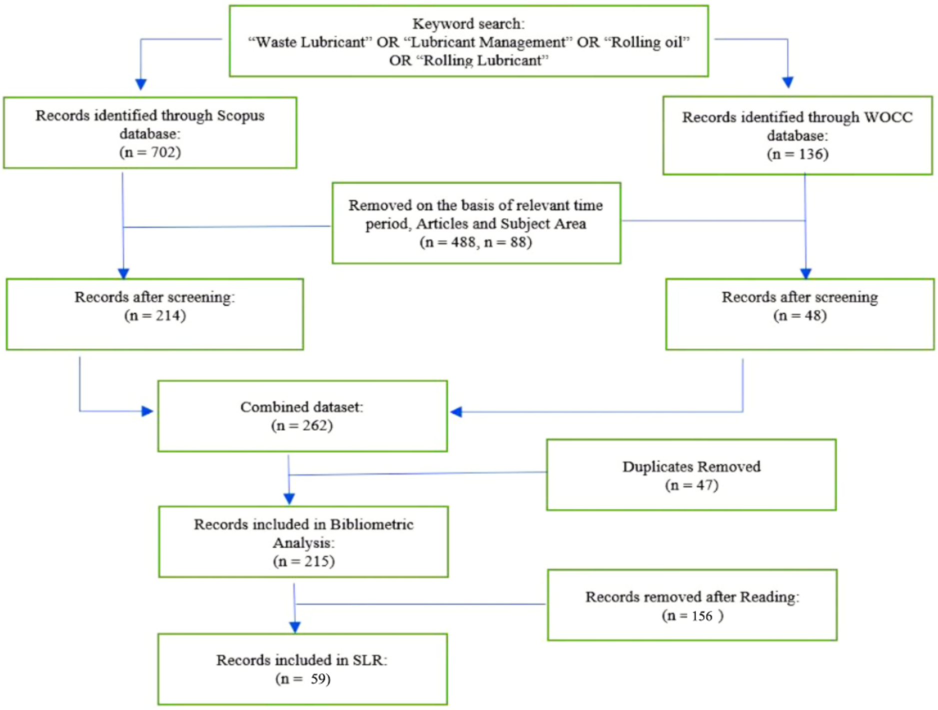

Figure:1 PRISMA Flow Chart

The bibliographic dataset was constructed using two leading academic databases, Scopus and the Web of Science Core Collection (WOCC), which together offer comprehensive coverage of peer-reviewed research outputs across scientific and engineering disciplines. The study followed the PRISMA guidelines to ensure methodological transparency and reproducibility in the literature selection process. An initial keyword search using the terms "Waste Lubricant," "Lubricant Management," "Rolling Oil," and "Rolling Lubricant" was conducted across the two major databases. The search identified 702 records from Scopus and 136 records from WOCC, yielding a total of 838 publications. In the screening stage, records were filtered based on the relevant publication period, document type, and subject area, which resulted in the exclusion of 488 Scopus records and 88 WOCC records. After this filtering, 214 Scopus and 48 WOCC papers remained, producing a combined dataset of 262 unique records. Following the removal of 47 duplicates, 215 records were used for bibliometric analysis, which facilitated an overview of publication trends, thematic clusters, and authorship networks. These documents formed the foundation for the bibliometric analysis. A subsequent full-text screening and critical evaluation of the bibliometric dataset were undertaken to assess the conceptual and methodological relevance of each paper to the study's research objectives. This detailed reading process resulted in the exclusion of 156 studies that did not meet the inclusion criteria, such as lack of empirical data, insufficient methodological rigor, or irrelevance to lubricant-waste management. Ultimately, 59 studies were selected for inclusion in the Systematic Literature Review.

Bibliometric mapping was conducted using Bibliometrix (R package) which is widely employed for quantitative literature analysis. The analysis considered multiple dimensions of scholarly output such as Annual scientific production, in order to trace the temporal evolution of research activity, Source analysis, to identify the core journals contributing to the field, Citation analysis, highlighting the most influential documents, authors, and countries and Keyword frequency and co-occurrence networks, to uncover dominant themes, research clusters, and emerging areas of interest.

Through this multi-dimensional analysis, the bibliometric component offered a systematic overview of the intellectual structure, thematic orientation, and geographical distribution of research in waste lubricant oil management.

The SLR was conducted using the TCCM framework (Theory–Context–Characteristics–Methodology). This framework facilitated a structured synthesis of: Theoretical foundations, including models of pyrolysis kinetics, solvent–solute interactions, biodegradation dynamics, and life cycle assessment. Contextual drivers, such as industrial applications in steel, automotive, energy sector and geographical case studies. Technological and process characteristics, spanning thermochemical, physicochemical, and biological pathways, as well as their trade-offs in efficiency, scalability, and environmental impact. Methodological approaches, including experimental designs, analytical characterization, kinetic modelling, and life cycle assessment techniques.

The integration of bibliometric analysis with an SLR offers several advantages. Bibliometric mapping provides a panoramic view of research evolution and intellectual structure, although the SLR allows for deeper, qualitative synthesis of the most thematically relevant studies. The use of the PRISMA framework enhances transparency and replicability in study selection, and the TCCM framework ensures a holistic synthesis across theoretical, contextual, technological, and methodological dimensions. This combined strategy therefore delivers a rigorous and multidimensional understanding of waste lubricant oil management research, bridging quantitative mapping with qualitative evaluation. The systematic synthesis enables an important evaluation of the field, integrating diverse disciplinary contributions as well as highlighting gaps and unresolved challenges.

4.1 Results and Discussion: Bibliometric Analysis

4.1.1 Annual Scientific Production

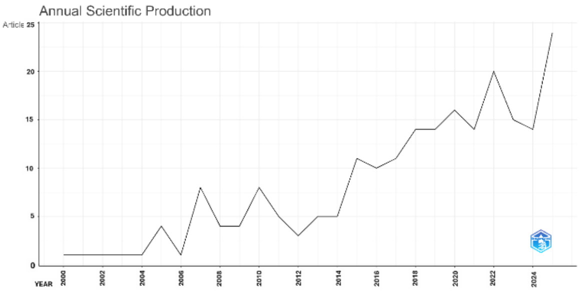

Figure: 2 Annual scientific production

The temporal analysis of annual scientific production represented by figure-2 highlights the evolution and growth trajectory of research activity. Between 2000 and 2010, publication output remained relatively modest, rarely exceeding 10 documents per year. This period can be characterized as the formative stage of the field, during which foundational theories and methods were being established.

From 2010 to 2015, the field exhibited gradual but fluctuating growth, with annual output ranging between 5 and 12 documents. This transitional phase suggests that even as the domain was gaining traction, it had not yet reached critical mass.

A significant turning point emerged after 2015, when the number of publications began to rise steadily, surpassing 15 annual outputs by 2019. The subsequent period from 2019 to 2022 marked a phase of consolidation and expansion, with output levels consistently above 15 documents, peaking at around 20 in 2021. Most strikingly, 2025 records the highest scientific production to date, with nearly 24 documents, reflecting an unprecedented surge of research interest.

This trajectory suggests that the domain has entered a mature and expanding stage, characterized by heightened academic attention, broader international engagement, and potentially greater industry relevance. The consistent growth also indicates that the field has moved beyond its formative phase and is now firmly positioned as an established area of inquiry, with increasing opportunities for cross-disciplinary collaboration.

4.1.2 Citation Trends: Evolution of Scholarly Impact

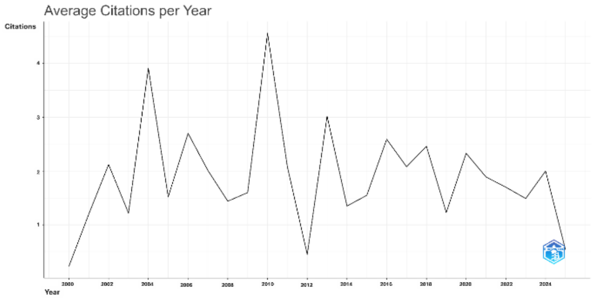

Figure: 3 Annual Citation per Year

The temporal analysis of average citations per year represented by Figure-3 illustrates the cyclical and uneven trajectory of scholarly influence. Peaks in citation averages are observed in 2004, 2010, and 2013, which likely correspond to the publication of seminal works or breakthrough studies that shaped subsequent research directions. These bursts of influence reflect the episodic nature of knowledge advancement in the domain, where landmark contributions periodically redefine scholarly debates.

Conversely, certain years such as 2012 and 2015 recorded lower citation averages, indicating periods of relative stagnation or incremental contributions. In the more recent years (2022–2025), citation averages appear to decline. However, this trend should be interpreted cautiously, as it is likely due to citation lag, with newer publications requiring time to accumulate scholarly attention.

The overall pattern indicates that the field does not follow a steady trajectory of growth in influence but rather alternates between periods of high and moderate impact. This oscillation underscores the importance of breakthrough studies in sustaining scholarly momentum and suggests that the field is shaped by pivotal contributions rather than continuous incremental development.

4.1.3 Country-Level Citation Analysis: Geographical Distribution of Impact

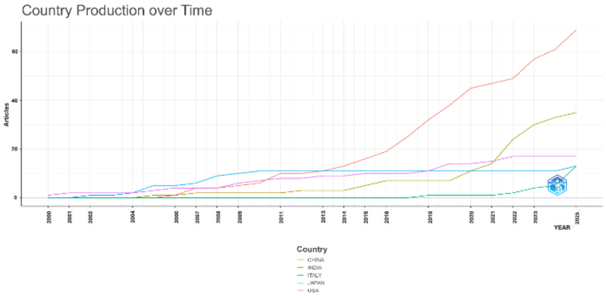

Figure: 4 Country Production over time

The country-level analysis represented by Figure-4 reveals the uneven distribution of scholarly impact across regions. South Africa (155 citations) and China (152 citations) emerge as leading contributors, surpassing even traditionally dominant research hubs such as the USA (108 citations) and the United Kingdom (99 citations). The strong citation performance of South Africa and China is notable, as it indicates the rising influence of non-traditional research centres in shaping global knowledge production. This trend may be linked to local industrial priorities, policy initiatives, and the increasing international visibility of researchers from these regions.

Canada (53 citations) occupies a middle position, followed by Japan (32 citations), the Netherlands (21 citations), India (19 citations), and Turkey (19 citations). Italy, with 12 citations, represents the lower end of the spectrum. Despite the fact that advanced economies such as the USA, UK, and Canada continue to exert considerable influence, the growing contributions of emerging economies (China, India, Turkey) and developing nations (South Africa) reflect the diversification of research leadership. This diversification suggests a shift from knowledge monopolies to more globally distributed networks of expertise.

Such geographical dispersion of citation impact also implies that the field is increasingly shaped by context-specific challenges and solutions. For example, South Africa's emphasis may stem from its industrial and environmental challenges related to oil management, whilst China's strong performance reflects its large-scale industrial base and significant investments in energy and material sciences.

4.1.4 Most Relevant Sources

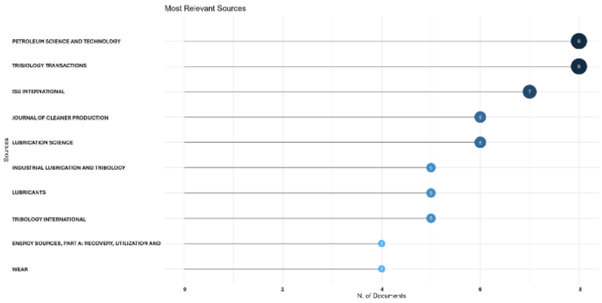

Figure: 5 Most relevant Sources

The distribution of documents across journals as represented by Figure- 5 sheds light on the publication outlets most actively contributing to the field's development. The findings reveal that the research output is concentrated in a cluster of specialized and applied journals. At the forefront are Petroleum Science and Technology and Tribology Transactions, each contributing 8 documents. These journals primarily focus on petroleum applications, lubrication, and tribology, reinforcing the applied orientation of the research landscape.

Close behind are ISIJ International with 7 documents and the Journal of Cleaner Production alongside Lubrication Science with 6 documents each. The presence of the Journal of Cleaner Production is particularly noteworthy, as it signals an emerging concern for sustainability and environmental considerations within a traditionally industrially oriented research area.

Additional relevant outlets include Industrial Lubrication and Tribology, Tribology International, Lubricants, and Wear, all of which are strongly associated with tribology, lubrication, and material performance. Collectively, this concentration demonstrates that the field is heavily aligned with engineering, applied physics, and industrial process optimization, also at the same time beginning to intersect with themes of sustainability and cleaner technologies.

Such clustering of sources indicates the development of a specialized yet interdisciplinary knowledge base, where engineering applications meet environmental and industrial performance concerns. For researchers, this implies that the most effective dissemination strategies involve targeting these leading journals, which serve as the central hubs of scholarly communication in the field.

4.1.5 Most Global Cited Documents

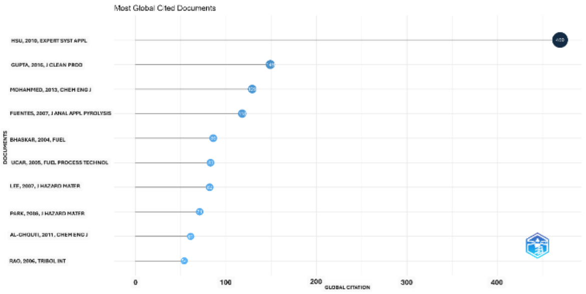

Figure: 6 Most Global Cited Documents

The analysis of the most globally cited documents represented by Figure-6 underscores the pivotal role of a limited number of highly influential studies in shaping the intellectual structure of the field. The most notable contribution "The Application of Fuzzy Delphi Method and Fuzzy AHP in Lubricant Regenerative Technology Selection" by (Hsu, 2010) in Expert Systems with Applications, which has accrued 469 citations, representing a clear outlier in terms of scholarly influence. This level of citation activity suggests that the work is not only foundational but also widely adopted across multiple streams of research. Its dominance indicates that it likely introduced a methodological innovation or conceptual framework that has since been referenced extensively.

The second tier of influential works includes “Recent developments in Sustainable Manufacturing of gears: A Review” by (Gupta, 2016) in Journal of Cleaner Production with 149 citations, “Waste lubricating oil treatment by Extraction and Adsorption” by (Mohammed, 2013) in Chemical Engineering Journal with 129 citations, and “Pyrolysis and Combustion of waste lubricant oil from diesel cars: Decomposition and Pollutants” by (Fuentes, 2007) in Journal of Analytical and Applied Pyrolysis with 118 citations. These documents have also exerted considerable influence, though at a lower scale compared to the 2010 landmark paper. Importantly, the citation distribution reveals a long-tail effect, where the majority of documents, such as “Recycling of waste lubricant oil into chemical feedstock or fuel oil over supported Iron Oxide Catalysts” by (Bhaskar, 2004) in Fuel (86 citations) and “A comparative study on the performance of Boric acid with several conventional lubricants in metal forming processes” by (Rao, 2006) in Tribology International (54 citations), attract moderate but sustained attention.

This uneven distribution highlights the presence of a citation concentration phenomenon, wherein a small proportion of documents generate a disproportionately large number of citations. Such patterns are common in emerging and applied research domains, where one or two highly cited studies act as intellectual anchors, although subsequent studies build incrementally upon their foundations.

4.1.6 Keyword Analysis:

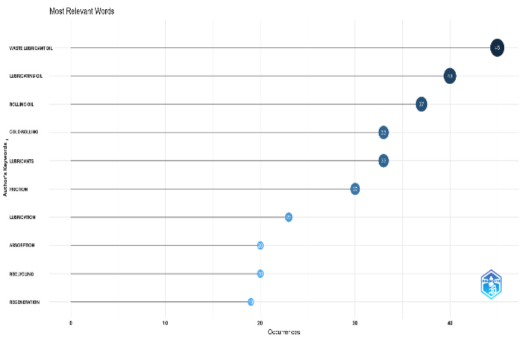

Figure: 7 Most Relevant Keyword

The keyword co-occurrence analysis represented by Figure-7 highlights the dominant research directions pursued by scholars. The most recurrent keywords, “waste lubricant oil” with 45 occurrences, “lubricating oils” with 40 occurrences, and “rolling oil” with 37 occurrences, indicate the field’s central concern with lubricant utilization and waste management. This suggests that much of the scholarly discourse is oriented towards the challenges of waste oil handling, recycling processes, and the optimization of lubricants for industrial use.

The presence of terms such as “cold rolling” with 33 occurrences, “lubricants” with 33 occurrences, and “friction” with 30 occurrences demonstrates the field’s close association with tribology and material processing, underscoring the dual emphasis on both application and performance. Importantly, keywords such as “adsorption”, “recycling”, and “regeneration” illustrate the emerging research strand directed towards sustainability. These terms point to efforts at developing eco-friendly approaches for lubricant recovery and waste minimization, reflecting the alignment of this domain with global environmental priorities.

Overall, the keyword analysis suggests a well-balanced research landscape: although established themes around lubricant performance and rolling processes dominate, there is also a discernible shift toward environmental and regenerative solutions. This dual orientation reflects the field’s evolution from a performance-driven to a sustainability-driven paradigm.

4.1.7 Keyword Co-occurrence Network Analysis

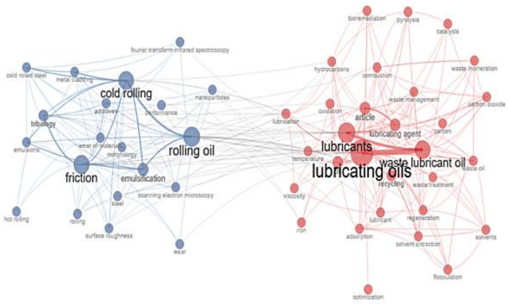

Figure: 8 Keyword Co-occurrence Network Analysis

The co-occurrence network represented by Figure-8 further refines the thematic structure of the field by clustering author keywords into interconnected domains. Two distinct but interconnected clusters are evident, reflecting complementary strands of research focus.

The first cluster (blue nodes) is centred around “rolling oil,” “cold rolling,” and “friction.” This group of terms is closely linked to tribological performance, material processing, and surface quality in rolling and lubrication systems. Keywords such as “tribology,” “emulsification,” “surface roughness,” and “wear of materials” highlight the technical dimension of lubricant use, particularly in the context of mechanical performance and process optimization. This cluster illustrates a strong industrial engineering orientation, where lubricants are primarily studied for their role in improving efficiency, reducing wear, and enhancing the quality of rolled products.

The second cluster (red nodes) revolves around “lubricating oils,” “waste lubricant oil,” and “lubricants.” The associated terms, including “recycling,” “regeneration,” “waste management,” “adsorption,” and “solvent extraction,” signify an environmental and sustainability-focused research direction. This cluster emphasizes processes for treating, reusing, and regenerating lubricant oils, as well as exploring eco-friendly disposal and recovery strategies. Subtopics such as “bioremediation,” “pyrolysis,” and “waste incineration” reflect attempts to address ecological risks associated with lubricant waste.

Interestingly, the two clusters are not isolated but are connected through bridging terms such as “lubrication” and “lubricating agent,” which serve as conceptual links between the performance-driven and sustainability-driven research agendas. This connection indicates that though the field is divided into technical and environmental domains, there is a growing recognition of their interdependence. For example, the development of efficient lubricants is increasingly evaluated not only in terms of tribological performance but also with respect to recyclability and ecological impact.

The size of the nodes and the density of connections further reinforce the dual emphasis of the field. Larger nodes such as “lubricating oils” and “waste lubricant oil” reflect core themes that anchor research, whilst more specialized nodes such as “nanoparticles” or “flocculation” point to emerging, niche directions within the broader domain.

Table: 1 Summary Matrix

Metrics	Details
Total Number of Papers	215
Publication Period	2000 – 2025
Most Cited Papers	The Application of Fuzzy Delphi Method and Fuzzy AHP in Lubricant Selection, Recent Developments in Sustainable Manufacturing, Waste Lubricating Oil Treatment by Extraction and Adsorption, Pyrolysis and Combustion of Waste Lubricant Oil, Recycling of Waste Lubricant Oil into Chemicals and Fuels, Copyrolysis of Scrap Tires with Waste Lubricant Oils, Degradation Characteristics of Waste Lubricant Oils, Electrokinetic Remediation of Contaminated Soils with Waste Oils, New Adsorbents Based on Microemulsion Modified Silica, Comparative Study on Boric Acid Esters as Lubricant Additives
Most Productive Journals	Petroleum Science and Technology, Tribology Transactions, ISIJ International, Journal of Cleaner Production, Lubrication Science, Industrial Lubrication and Tribology, Tribology International, Lubricants, Energy Sources, Wear,
Most Common Keywords	Waste Lubricant Oil, Lubricating Oils, Rolling Oil, Cold Rolling, Lubricants, Friction, Lubrication, Adsorption, Recycling, Regeneration

4.2 Results and Discussion: Systematic Literature Review (TCCM Framework)

4.2.1 Theory Segment

(a) Tribology and Surface-Film Theories

Tribological theory forms the basis for understanding friction, wear, and surface-film formation in metallic and rolling-contact systems, processes essential to lubricant formulation and waste-oil reuse. Recent studies advanced oil-free lubrication theory [1], showing that aqueous oil-free systems can achieve friction levels comparable to oil-in-water emulsions through the formation of stable boundary films. This framework was further expanded using biodegradable emulsions [2], emphasizing that film stability and surface reusability govern tribological efficiency and water-recovery performance. Nanotribological transformation theory demonstrated that MoS_2 nanoparticles oxidize to MoO_3 under rolling contact yet maintain lubricity via self-regenerating oxide layers [3]. Lubricant-reuse dynamics were later introduced [4], showing that impurity control and periodic replenishment preserve boundary-film integrity during recycling. Super lubricity concepts further revealed that DLC films and nanomaterials can achieve ultralow friction in rolling/sliding contacts [5]. Collectively, the literature identifies interfacial chemistry, nanoparticle transformation, and film architecture as critical determinants in next-generation lubrication and reuse systems.

(b) Reaction-Kinetics and Catalytic-Conversion Theories

Chemical-kinetics and catalytic-conversion theories provide insight into molecular mechanisms governing conversion efficiency and product selectivity during thermochemical processing of lubricant waste. Activation-energy distributions for rolling-oil-sludge pyrolysis were determined using OFW, Friedman, and KAS models [6]. Catalytic-pyrolysis selectivity theory established that CeO_2/Al_2O_3 catalysts promote C–C bond cleavage and desulfurization [7]. Two-stage pyrolytic upgrading was shown to yield fuels comparable to diesel [8]. Co-pyrolysis synergy revealed radical-chain interactions between waste rubber and lubricant oils that enhance hydrocarbon output [9]. Catalytic-reforming theory demonstrated that Ni-dolomite improves water–gas-shift reactions and optimizes H_2/CO ratios [10]. Thermo-oxidative degradation theory linked oxidation kinetics to polymerization, molecular-weight growth, and sludge formation [11].

These developments align with earlier catalytic studies, which demonstrated that catalyst composition, temperature, and reaction environment dictate hydrocarbon cracking and product yield [12, 13,14] . Zeolite-based catalysis further confirmed these mechanisms [15]. Together, these contributions establish a unified kinetic–catalytic framework in which catalyst microstructure and reaction thermodynamics jointly govern WLO conversion.

(c) Environmental Biotechnology and Biodegradation Theory

Biodegradation theory is grounded in microbial ecology, enzymatic-kinetics modelling, and biosurfactant-assisted solubilization. Complete degradation of lubricant waste by *Scenedesmus vacuolatus* and mixed microalgae was demonstrated, supporting microbial accumulation and hydrocarbon assimilation theory [16]. Biosurfactant-enhanced degradation was observed with *Achromobacter xylosoxidans*, which uses glycolipid production to decompose hydrocarbons and phthalates [17]. Additional microbial pathways showed that *Achromobacter aegrifaciens* metabolizes kerosene-based rolling oils via oxidation–methylation mechanisms [18]. Earlier biodegradation models used Haldane kinetics and Box–Behnken design to optimize process conditions [19, 20]. Collectively, these findings highlight that microbial systems serve as biocatalytic platforms capable of converting hydrocarbons into non-toxic end-products.

(d) Separation, Extraction, and Regeneration Theories

Separation-process theory, adsorption principles, and solvent-extraction modelling are widely used in lubricant regeneration. Polymeric flocculation–adsorption mechanisms demonstrated that PDADMAC effectively neutralizes and removes colloidal impurities [4]. Ultrasonic-assisted solvent extraction enhanced mass transfer due to cavitation-driven turbulence [21]. Adsorption-clarification using melamine–silica networks increased surface area and impurity capture [22]. Supercritical-solubility models correlated CO_2 density with hydrocarbon solubility, supporting green-extraction design [23].

These contributions extend classical regeneration research, which demonstrated that mass-transport dynamics, sorption isotherms, thermophysical transport properties, and membrane pore structure govern WLO purification performance.

(e) Combustion, Engine-Performance, and Thermodynamic Theories

Combustion and thermodynamic theories support the development of waste-oil-derived fuels. Hydrogen-assisted combustion increases thermal efficiency and reduces smoke emissions [29]. Compression-ratio optimization showed improved brake thermal efficiency in diesel blends with waste transformer oil [30]. Spray–swirl interaction theory linked emissions behaviour to atomization geometry and turbulence [31]. Detonation-performance theory confirmed safe and effective substitution of diesel with waste oil in ANFO explosives [32]. Collectively, these works connect molecular-scale combustion chemistry with engine-level performance.

(f) Materials Recovery, Nanostructure, and Magnetic-Separation Theories

Materials-recovery approaches draw on nanostructure formation, autocatalysis, and magnetic-separation principles. Autocatalytic hydrodeoxygenation demonstrated that in-situ Fe/Fe_3O_4 nanoparticles catalyse hydrocarbon formation while enabling magnetic self-separation [33]. Magnetically assisted catalysis showed that Fe_3O_4 recovered from rolling-mill sludge accelerates reduction reactions [34]. Industrial co-processing integrated rolling-mill sludge into iron-ore sintering for simultaneous disposal and resource recovery [35]. Asphalt-rejuvenation theory proposed that waste rolling oils enhance binder stiffness and pavement longevity [36, 37]. These advances connect lubricant waste chemistry with metallurgical and civil-engineering performance.

(g) Circular-Economy and Lifecycle Theories

Circular-economy and LCA frameworks evaluate sustainability trade-offs in waste-lubricant systems. Regeneration pathways such as hydro-treatment and solvent extraction were shown to outperform incineration on climate metrics [38]. National waste-oil management models highlighted dependency on process mix and collection rates [39]. Integrated approaches to aviation-lubricant recycling further expanded lifecycle understanding [40]. Foundational LCA studies provided early frameworks emphasizing waste hierarchy and stewardship [41,42]. Together, these works situate WLO management within a systems-optimization perspective balancing environmental and economic objectives.

(h) Data-Driven and Analytical-Modelling Theories

Recent advancements apply chemometrics and deep learning to lubricant degradation and recovery. Hybrid CNN–interval-PLS models improved spectral prediction and process monitoring [43]. These complement earlier kinetic and statistical models, marking a shift toward AI-assisted optimization in lubricant regeneration [19, 20, 24].

(i) Integration and Theoretical Gap

Current scholarship integrates tribology, catalysis, biodegradation, separation science, materials recovery, combustion, and lifecycle analysis into a multiscale theoretical framework. Foundational theories (2009–2020) [27, 28, 44], have been extended in recent work (2021–2025) [34, 35, 37, 38], to include nanostructure formation, hybrid catalysis, chemometrics, and circular-economy modelling. However, a key theoretical gap persists: few studies couple micro-scale reaction and tribological phenomena with macro-scale technoeconomic and policy models. Future frameworks should integrate molecular, process, and lifecycle scales to guide next-generation WLO management.

4.2.2 Context Segment

Research on waste lubricant oil (WLO) regeneration, treatment, and reuse spans a wide range of industrial, environmental, and technological contexts, highlighting its cross-sectoral relevance and increasing global urgency. The progression of this literature—from early analytical studies on oil purification and catalytic cracking to recent multi-sectoral applications in energy recovery, materials engineering, and circular economy frameworks—demonstrates how WLO management has evolved into a focal point of sustainability innovation and industrial transformation.

a) Industrial and Manufacturing Contexts

A substantial body of WLO research originates from steel and metallurgical manufacturing environments,

where cold-rolling oils, machining fluids, and emulsions present persistent challenges related to waste generation and process efficiency. Recent studies in European steel-rolling mills examined the adoption of oil-free and biodegradable lubricants, aligning with the European Green Deal's decarbonization objectives [1, 2]. Complementary work in East Asian industrial settings explored nano-enhanced lubricants and recycled tempering oils tested under actual production conditions[3, 4]. Additional studies situated within large Chinese integrated steel complexes investigated pyrolysis and sintering co-processing of rolling-oil sludge as waste-valorisation pathways[6, 35].

Earlier research reflects similar industrial imperatives. Membrane bioreactors were applied to rolling-mill wastewater treatment [45, 46] and microbial degradation of kerosene-based rolling oils was demonstrated in industrial effluents [18]. Regenerated lubricants were used as fuel in aluminium smelting, while lubricant recovery in industrial furnace systems was documented [47] Together, these studies underscore the dual pressures of operational efficiency and waste minimization within continuous manufacturing systems—pressures increasingly driven by environmental regulations and technological modernization.

b) Energy and Fuel-Conversion Contexts

A second major contextual cluster reframes WLO as a secondary energy resource. Studies demonstrated that pyrolyzed waste-oil blends and hydrogen co-firing can improve internal combustion engine performance and reduce emissions [8, 29, 30]. Catalytic pyrolysis and steam-reforming experiments using modified catalysts produced diesel-like fuels and syngas with significantly lower sulphur content [7, 9, 10]. Further applications extended into combustion and explosives engineering, demonstrating the feasibility of WLO-derived fuels in industrial systems [31, 32].

These advances build upon earlier regeneration efforts using zeolite-based catalysts to recover fuel-quality hydrocarbons [12, 15]. Collectively, this body of work positions WLO energy recovery within the broader global agenda of energy transition, decarbonization, and circular utilization of industrial byproducts.

c) Environmental and Remediation Contexts

Environmental and remediation contexts dominate contributions from both developing and industrialized regions. Microbial and bacterial degradation of hydrocarbon pollutants was investigated in African and South Asian systems, supporting eco-restoration and water-protection goals [16, 17]. Polymeric adsorption and ultrasonic solvent-extraction methods were analysed for treating lubricant-contaminated wastewater, with emphasis on integration into industrial treatment infrastructure [4, 21, 22, 48].

Earlier environmental studies addressed drilling waste management, electrokinetic soil remediation, and advanced oxidation using microbubble ozonation for degrading waste-oil distillates [45, 49, 50]. Collectively, this literature indicates a transition from end-of-pipe waste handling to circular recovery systems, aligning with global commitments such as SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action).

d) Construction and Materials-Reuse Contexts

A rapidly growing research frontier connects WLO reuse with construction-material innovation. Waste rolling oils and re-refined oil residues were shown to enhance rheological and mechanical performance of asphalt binders [36, 37], contributing to circular-construction approaches in Middle Eastern and European contexts. Nanostructured materials recovery has also been explored, particularly the transformation of iron-rich rolling-mill sludge into magnetic Fe_3O_4 catalysts [33, 34]. These advancements extend WLO management beyond environmental protection toward value-added infrastructure and materials applications.

e) Analytical, Policy, and Systems Contexts

At the policy and systems-analysis level, WLO management is increasingly embedded within environmental governance and lifecycle frameworks. European and Eastern European waste-oil scenarios were modelled using LCA and ReCiPe methodologies, comparing regeneration, incineration, and co-processing options [38, 39, 40]. Foundational sustainability and lifecycle models were developed, while industry-led stewardship initiatives were documented in New Zealand [24, 41, 51].

In analytical chemistry and data science, machine learning and chemometric models were introduced to support lubricant quality monitoring and predictive degradation assessment [43]. Collectively, these contributions reflect an evolution from purely technical research to a multi-stakeholder systems problem integrating industry, regulation, and digital analytics.

f) Geographical and Temporal Scope

The reviewed literature spans diverse global regions and a significant temporal range. European contributions highlight advanced policy-driven decarbonization initiatives [1, 2, 37, 38]. Asian research emphasizes industrial innovation in pyrolysis and resource recovery [3, 10, 34, 35, 52]. Middle Eastern studies, African research, and South American studies address region-specific waste challenges [8, 16, 22].

Temporally, the literature spans 2009–2025, progressing from early efficiency-driven studies (2009–2015) to sustainability-oriented, circular-economy approaches (2016–2025). This shift aligns with global post–Paris Agreement commitments and increasing industrial focus on waste valorisation.

g) Cross-Sectoral Integration

Across these varied contexts, a consistent trend emerges: WLO is increasingly recognized not as a pollutant but as a recoverable secondary resource. Advances in tribology, catalytic thermochemistry, biotechnology, and lifecycle modelling collectively demonstrate that WLO challenges are technologically solvable yet systemically complex [1, 6, 16, 41]. Effective solutions require cross-sectoral coordination among industrial operators, environmental regulators, and scientific communities.

Thus, the contextual evolution of WLO research mirrors broader global transitions toward resource circularity, decarbonization, and digital process integration—positioning waste-lubricant management as both an environmental necessity and an opportunity for sustainable industrial transformation.

4.2.3 Characteristics Segment

The consolidated literature on waste lubricant oil (WLO) regeneration, treatment, and reuse demonstrates a clear progression from laboratory-scale experimentation toward multi-scale, data-driven, and policy-integrated research. Across the 59 studies reviewed, several methodological clusters emerge—encompassing tribological testing, catalytic conversion, biological degradation, material recovery, and lifecycle assessment. Together, these works depict an interdisciplinary research field bridging chemical engineering, materials science, biotechnology, environmental science, and policy analysis.

a) Experimental and Laboratory-Based Studies

Approximately two-thirds of the reviewed studies rely on laboratory-scale experimentation to evaluate physicochemical properties, reaction kinetics, tribological performance, and fuel-reuse feasibility. Pilot tribological tests conducted in controlled rolling environments validated biodegradable and oil-free lubricants[1, 2]. Nanoparticle-enhanced lubrication systems were extensively investigated, employing tribometers, SEM, TEM, and surface-profiling tools to characterize film morphology, wear scars, and frictional behaviour [3, 5, 52].

Thermochemical and kinetic studies examined pyrolysis, catalytic cracking, and reforming of WLO under controlled conditions. Researchers applied TGA, OFW, Friedman, and related kinetic models to derive activation energies and reaction pathways [6, 7, 9]. Bench-scale engine tests combined with combustion emission monitoring assessed performance, fuel efficiency, and pollutant emissions of WLO-derived fuels [8, 29, 30].

Earlier foundational experiments using mesoporous silica catalysts and zeolites optimized cracking and pyrolysis of WLO [12, 13, 15]. These studies emphasized precise manipulation of temperature, catalyst ratios, and reaction times, validated through GC–MS, FTIR, TGA, and chromatography. Collectively, these works form the empirical backbone of WLO research, testing and validating theoretical assumptions regarding lubrication behaviour, chemical transformation, and emissions under controlled conditions.

b) Process Modelling and Optimization Studies

A growing segment of the literature integrates computational modelling, chemometric analysis, and optimization frameworks. Deep-learning neural networks combined with partial least squares (PLS) were introduced to enhance spectral modelling and lubricant

classification [43, 53]. Kinetic and catalytic reforming models simulated syngas yield optimization, while oxidation–degradation models characterized lubricant aging and sludge formation [10, 11].

Policy–engineering interface studies applied systems-level modelling to evaluate environmental outcomes. ReCiPe 2016–based lifecycle scenarios were developed [39], and multi-objective optimization models assessed environmental and economic trade-offs in EU waste-oil recovery pathways [38]. Earlier modelling efforts included fuzzy axiomatic design for regeneration-technology selection and regression-based thermophysical property estimation [25, 54]. These contributions illustrate a broader transition from purely experimental investigations toward predictive modelling and systems optimization, supporting industrial-scale decision-making and policy formulation.

c) Biotechnological and Environmental Studies

A distinct subset of studies focuses on biodegradation, bioremediation, and environmentally friendly treatment strategies. Microalgal degradation of WLO using *Scenedesmus vacuolatus* was demonstrated, with detailed measurements of hydrocarbon breakdown and nutrient uptake kinetics [16]. Biosurfactant-assisted hydrocarbon degradation was observed in *Achromobacter xylosoxidans*, while *Achromobacter aegrifaciens* displayed similar metabolic capacity [17, 18]. Earlier biodegradation studies combined Haldane kinetics and Box–Behnken experimental design to optimize substrate inhibition and degradation performance [19, 20].

Environmental-engineering approaches applied physicochemical regeneration methods such as polymeric flocculation–adsorption, ultrasonic solvent extraction, and melamine–silica adsorption–clarification [21, 22, 52]. Earlier analogues include modified sawdust adsorption and colloidal stability studies [27, 44]. Collectively, these studies demonstrate that bio-assisted and eco-compatible strategies can complement conventional chemical treatments, supporting circular-bioeconomy principles and SDG-aligned remediation pathways.

d) Material-Recovery and Product-Reuse Studies

The emergence of material-recovery research reflects a shift from remediation toward resource valorisation. Magnetic separation and nanostructured Fe_3O_4 catalyst formation was demonstrated, enabling pollutant reduction and catalytic reuse [33, 34]. Sintering co-processing studies integrated rolling-oil sludge into iron-ore sintering operations, contributing both carbon and iron while minimizing waste [35].

Civil-engineering applications incorporated re-refined oils and lubricant residues into asphalt binders, improving durability and mechanical performance [36, 37]. Earlier industrial applications include the use of regenerated WLO as smelting fuel and lubricant performance assessments in metal treatment [47]. These studies establish a circular-materials perspective, converting industrial pollutants into feedstocks for metallurgical, catalytic, and infrastructure applications.

e) Policy, Lifecycle, and Circular-Economy Studies

At the systems scale, lifecycle analysis (LCA), policy frameworks, and economic modelling are increasingly applied. Multi-criteria assessments evaluated environmental trade-offs among regeneration, co-processing, and incineration pathways [38–40]. Foundational LCA frameworks linked efficiency with sustainability metrics [24, 41]. Decision-support tools integrating fuzzy logic and stewardship policy analyses further strengthened strategic planning for WLO management [42, 54].

At the industrial-process level, solvent safety and emission-management frameworks were developed, while AI-based spectral modelling supported real-time quality control [7, 43, 55]. Together, these studies highlight the importance of aligning technology with sustainability policy and circular-economy imperatives.

f) Research Design and Data Characteristics

Across the literature, research designs are predominantly quantitative and experimental (≈60%), followed by computational or statistical modelling (≈20%), biotechnological/environmental analyses (≈10%), and policy/LCA studies (≈10%). Sample sizes vary widely—from microreactors (<50 mL) to industrial rolling-mill pilot trials. Analytical tools frequently include FTIR,

GC–MS, SEM–EDS, TGA, UV–Vis, XRD, and particle-size analysis. Statistical and computational methods such as regression analysis, ANOVA, ANN modelling, kinetic simulation, and lifecycle impact assessment are widely applied.

The dataset displays methodological heterogeneity ranging from single-factor laboratory studies to integrated multi-criteria systems models. This methodological diversity enhances data robustness, reproducibility, and cross-study comparability, while broadening the empirical foundation for WLO research.

g) Outcome Characteristics and Contribution Patterns

Outcome patterns reveal predominance of proof-of-concept and feasibility studies, with relatively limited long-term or field-scale validation. Significant improvements in friction reduction, wear performance, and combustion behaviour were reported [1, 3, 8], while effective pollutant mitigation and material recovery were demonstrated [6, 33]. Earlier work similarly produced strong laboratory outcomes but limited industrial-scale translation [20, 46].

Lifecycle and sustainability assessments consistently show that environmental benefits depend strongly on regional energy mixes, infrastructure readiness, and policy support [38, 39, 41]. Overall, the literature reflects technological maturity at laboratory and pilot scales but remains fragmented regarding system-level integration, cross-sector scaling, and digitalization—highlighting opportunities for industrial deployment, cross-sector demonstrations, and data-driven optimization of WLO regeneration technologies.

4.2.4 Methodology Segment

Methodological diversity defines the literature on waste lubricant oil (WLO) regeneration, reuse, and treatment, with studies spanning laboratory experimentation, process modelling, lifecycle assessment, and biotechnology. Over time, research has evolved from small-scale physical and chemical experiments to multi-instrumental, computational, and sustainability-oriented frameworks, reflecting the field's maturation toward integrated circular-economy assessment.

a) Experimental Research Designs

Approximately 70% of studies employ quantitative, laboratory-based experimental designs to evaluate physicochemical, tribological, and catalytic behaviour of lubricant wastes. Oil-free and biodegradable lubrication trials were conducted under cold-rolling conditions, with friction, wear, and film durability measured using tribometers [1, 2, 56]. Nanoparticle-enhanced lubricants were examined using SEM, AFM, and EDS to characterize film morphology and oxide-layer evolution [3, 5].

Thermal and catalytic studies—including pyrolysis and reforming—applied thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) to derive activation energies and decomposition kinetics [6, 7, 9]. Engine-testing protocols combined with emissions monitoring evaluated brake thermal efficiency, CO_2 output, and combustion stability for pyrolyzed or blended WLO-derived fuels [8, 29, 30].

Earlier experimental contributions focused on catalyst design and process optimization, forming the empirical foundation for later tribological and kinetic frameworks [14, 15, 27]. Collectively, these experiments provide essential verification for theoretical models across tribology, catalysis, and environmental engineering.

b) Analytical and Instrumental Techniques

The literature demonstrates significant instrumental sophistication, integrating spectroscopic, microscopic, chromatographic, and thermo-analytical tools to ensure precision and reproducibility. FTIR and UV–Vis spectroscopy were used to detect oxidation products and functional-group transformations [3, 11]. GC–MS analysis quantified hydrocarbon composition and impurity levels in regenerated lubricants [7, 8].

Tribological characterization incorporated SEM, EDS, and 3D surface profilometry [1, 2], while thermal-degradation studies used TGA and DSC [6, 9]. Materials-recovery work employed XRD and vibrating-sample magnetometry (VSM) to characterize Fe_3O_4 nanoparticles [33, 34].

Earlier analytical contributions included FTIR, XRF, UV–Vis, and COD measurements [45, 55, 57]. This multi-instrumental trend underscores the field's reliance

on quantitative accuracy, cross-validation, and analytical rigor.

c) Modelling and Process Optimization Approaches

A major methodological advancement involves the integration of modelling, simulation, and optimization frameworks. Pyrolysis kinetic parameters were computed using OFW, Friedman, and KAS models [6]. Arrhenius-based kinetic modelling was employed to estimate selectivity and conversion efficiency in catalytic reforming [7, 10]. Oxidation-degradation models were developed to predict lubricant aging under thermal stress.

Computational methods further expanded the methodological landscape: deep learning and interval-PLS were applied for spectral prediction; LCA-based multi-criteria optimization was conducted for waste-oil regeneration scenarios [38, 39, 43]. Fuzzy design and thermophysical regression models provided earlier precursors to modern optimization tools [25, 54]. These modelling approaches reflect a shift toward predictive, data-driven, sustainability-oriented process design.

d) Environmental and Lifecycle Assessment Frameworks

Lifecycle assessment (LCA) and environmental modelling play an increasingly central methodological role. ISO 14040-compliant LCA models compared regeneration, incineration, and co-processing pathways [38]. National-scale recycling scenarios were evaluated using ReCiPe 2016 categories [39]. Energy and emissions modelling assessed aviation lubricant recycling [40].

Industrial co-processing and asphalt-reuse studies incorporated lifecycle indicators [35, 36], linking environmental impacts with process performance. Foundational studies established conceptual bases for policy-oriented lifecycle modelling, emphasizing the waste hierarchy and sustainability metrics [41, 51]. Together, these frameworks signal a methodological convergence between process engineering and sustainability science.

e) Biotechnological and Environmental Treatment Methods

Biotechnological methods involve microbial and algal degradation of lubricant waste. Batch-culture degradation using *Scenedesmus vacuolatus* demonstrated significant hydrocarbon reduction over multi-week periods [16, 58]. Biosurfactant-assisted degradation by *Achromobacter xylosoxidans* quantified glycolipid production and pollutant breakdown [17, 59]. Similar biodegradation outcomes were reported for *Achromobacter aegrifaciens* [18].

These methods complement physicochemical regeneration approaches including ultrasonic extraction, adsorption–clarification, and polymeric flocculation–adsorption [4, 21, 22]. Earlier eco-compatible treatments such as electrokinetic remediation and drilling-waste management validated the viability of biological and physicochemical hybrid approaches [49, 50]. Together, these studies highlight environmentally aligned, low-energy alternatives for WLO detoxification.

f) Data-Driven and Simulation-Based Methodologies

Recent years have seen rapid adoption of AI, machine learning, and simulation-based research. Convolutional neural networks (CNNs) and interval PLS were used for spectral classification and lubricant-quality prediction [43]. Response Surface Methodology (RSM) was applied to optimize solvent extraction and adsorption processes [21, 22].

Thermodynamic simulations modelled CO_2 solubility in hydrocarbon systems to enable solvent selection and green extraction [55].

These methods represent a shift toward digital modelling, predictive analytics, and real-time process design, supporting scalable and industrially integrated WLO regeneration.

g) Methodological Trends and Research Gaps

Several methodological patterns and gaps emerge across the literature:

- Laboratory-scale studies dominate, while pilot- or industrial-scale validations remain limited [1, 3].
- Integration of environmental, tribological, catalytic, and techno-economic datasets is still uncommon, with only a subset employing comprehensive sustainability assessment frameworks [38, 39].

- Application of AI and machine learning—despite promising results it remains in early development [43].

Future research should prioritize multi-scale experimentation, real-time monitoring, and multi-objective optimization to more fully capture micro-level chemical transformations and macro-level environmental outcomes. Methodological integration across tribology, catalysis, biotechnology, and policy modelling will be essential for enabling WLO valorisation as a scalable, circular, and industry-aligned system.

5. Policy Implications for Advancing Circularity in Waste Lubricant Oil Management

The systematic review of Waste Lubricant Oil (WLO) management research reveals a consensus favouring regeneration and high-yield conversion technologies, primarily due to their superior environmental performance (as confirmed by LCA). To effectively harness these technological advancements and drive the circular economy, policy frameworks must evolve from simple disposal regulation to comprehensive, market-shaping mechanisms. The primary policy implications revolve around three pillars: reinforcing the waste hierarchy, optimizing economic incentives, and implementing extended producer responsibility (EPR) schemes.

5.1 Reinforcing the Waste Hierarchy and Regulatory Standards

The most immediate policy action must be the legislative enforcement of the waste management hierarchy, prioritizing regeneration (re-refining) over energy recovery (burning as fuel) and strictly prohibiting illegal dumping. Although many jurisdictions, such as the European Union, have policies demanding this prioritization, the research shows energy recovery often remains the economically easier, thus dominant, route in many regions.

Policy Directives:

I. Mandatory Regeneration Quotas: Governments should establish mandatory minimum content quotas for regenerated base oils in new lubricant formulations, similar to policies seen for recycled plastics and textiles. This creates guaranteed demand, stabilizes the market for re-refiners, and provides a clear incentive for investment in sophisticated regeneration facilities.

II. Quality Standardization: Policies must harmonize the standards for regenerated Group I, II, and III base oils with those of virgin oils. Regulators need to develop certification and testing protocols to ensure products from advanced regeneration technologies (like hydro-treatment and solvent extraction) meet stringent quality criteria, thus overcoming market hesitation from lubricant blenders.

III. Ban on Mixing: Strict regulations must be enforced to prevent the mixing of WLO with other hazardous wastes or low-quality fuels. Contamination significantly degrades the WLO feedstock, making regeneration economically unviable. Policy must support the separate collection cluster identified in the research to maintain feedstock purity.

5.2 Optimizing Economic Instruments and Investment

Research confirms that although regeneration has lower societal costs and greenhouse gas emissions than incineration, the initial capital investment and operational complexity remain high. Policy must bridge this economic gap through targeted fiscal mechanisms.

Policy Directives:

I. Eco-Modulated Fees: Introduce a progressive taxation system where producers are charged an "eco-contribution fee" based on the long-term environmental cost of their product. This fee should be modulated to be significantly higher for virgin oils and lower or zero for regenerated or bio-based lubricants (which represent the "Eco-Friendly Lubricant Development" cluster). This approach, known as eco-modulation, directly internalizes the externalities.

II. Capital Investment Subsidies: Direct public funding or tax credits should be allocated to pilot-scale and full-scale industrial trials, specifically for advanced, green-solvent-based

regeneration and catalytic pyrolysis technologies. This supports the Methodological Approaches identified in the research, helping companies de-risk the transition from laboratory validation to commercial operation.

III. Green Procurement Mandates: Government agencies, municipalities, and state-owned enterprises should be mandated to purchase lubricants and industrial oils with a minimum percentage of regenerated or bio-based content, creating a stable public market foundation for sustainable products.

5.3 Implementing Extended Producer Responsibility (EPR)

The most impactful systemic policy is strengthening the Extended Producer Responsibility (EPR) framework for lubricant oils. EPR shifts the financial and physical burden of end-of-life management from the taxpayer and local government to the original producer.

Policy Directives:

I. Full Cost Internalization: EPR programs must require producers to cover the entire cost of WLO collection, transport, and environmentally sound treatment, guaranteeing that regeneration is prioritized over cheaper, polluting alternatives.
II. Focus on Collection Infrastructure: Given that a significant percentage of WLO remains uncollected or illegally disposed of globally, EPR funds must be explicitly earmarked for developing comprehensive, spatially inclusive collection infrastructure, particularly in remote areas or from small, scattered waste holders.
III. Digital Traceability and Accountability: Leveraging digital platforms to track the entire WLO chain—from the point of sale (where the EPR fee is collected) to the re-refinery (where the material is certified)—is essential. This traceability ensures accountability, prevents illegal market activities (like unauthorized blending or burning), and provides the necessary data for LCA validation and policy impact assessment.

Finally, the policy future of WLO management lies in translating the theoretical and technological superiority of regeneration into a mandated economic reality. By combining mandatory regeneration quotas with targeted financial incentives and a strong, well-funded EPR system, policymakers can effectively guide the global lubricant industry toward a circular model, minimizing environmental harm and conserving finite resources.

6. Summary

The paper investigates the evolution and structure of Waste Lubricant Oil (WLO) management research through a dual methodology of bibliometric analysis and a Systematic Literature Review (SLR).

6.1 Intellectual Landscape (Bibliometric Analysis)

Production: Research output remained modest before 2010 but showed a significant surge after 2015, peaking in 2025, indicating the field's entry into a mature and expanding stage. Influence: Citation trends are episodic, with influential studies published in 2004, 2010, and 2013 creating "bursts of influence".

Geography: South Africa and China are the leading countries by citation count, suggesting the rising global influence of non-traditional research centres alongside established hubs like the USA and UK.

Thematics: The most relevant sources are specialized and applied journals like Petroleum Science and Technology and Tribology Transactions. The keyword analysis and co-occurrence network reveal two main, interconnected research clusters:

Performance-Driven: Focused on rolling oil, cold rolling, friction, and tribology.

Sustainability-Driven: Focused on waste lubricant oil, recycling, regeneration, waste management, and adsorption.

6.2 Thematic Landscape (Systematic Literature Review - TCCM Framework)

Theory: The research is grounded in the Circular Economy model, shifting the view of WLO from pollutant to a valuable secondary raw material. Key concepts include industrial symbiosis, life-cycle assessment (LCA), green chemistry, and bioremediation kinetics.

Context: Research is situated across three primary contexts:

- Industrial: Specifically, the steel and metal processing industry (e.g., cold rolling oil sludge).
- Energy/Fuel Recovery: Treating WLO as a feedstock for energy generation (e.g., pyrolysis, hydrocracking).
- Environmental Remediation: Using biological or physicochemical methods for detoxification in contaminated environments.

Characteristics: Dominant technological pathways include:

Regeneration and Solvent-Based Recovery: Focused on achieving high-quality base oils with a focus on solvent selection and product quality (e.g., viscosity index, flash point).

Thermo-chemical Conversion: Using catalysis (Ni, Fe, CeO_2) and kinetic models (OFW, KAS) to produce liquid fuels.

Life-Cycle and Policy Analysis: Employing LCA, LCC, and Multi-Criteria Decision-Making (MCDM) to assess environmental and economic trade-offs.

Methodology: The field relies heavily on experimental laboratory designs (reactor-analysis framework) and specialized analytical instrumentation (FTIR, GCMS, ICP). A crucial recent methodological trend is the transition to pilot-scale and industrial validation to ensure scalability, complemented by computational methods like LCA modelling and kinetic simulations (OFW, KAS).

6.3 Critical Gaps and Implications

Research Gaps: Major challenges are achieving industrial scalability for regeneration technologies, standardizing diverse methodologies, and fully assessing the long-term environmental trade-offs of energy recovery pathways.

Policy Implications: Policy must move beyond waste control to a resource-centric hierarchy that mandates and incentivizes the highest-value recovery, prioritizing regeneration before energy recovery, supported by an Extended Producer Responsibility (EPR) scheme.

7. Conclusion:

This study successfully mapped the intellectual and thematic landscape of Waste Lubricant Oil (WLO) management research by integrating bibliometric analysis and a Systematic Literature Review (SLR) using the TCCM framework, thereby addressing all stated objectives.

The bibliometric component achieved the objective of mapping the field by identifying an expanding research domain, characterized by an unprecedented surge in scientific production since 2015. The analysis revealed a significant geographical diversification of impact, with emerging economies, particularly South Africa (155 citations) and China (152 citations), shaping the global discourse alongside established hubs. The thematic map confirmed the existence of two interconnected intellectual clusters: one focused on tribological performance (For example, cold rolling, friction) and the other on environmental recovery and sustainability (For example, recycling, regeneration).

The Systematic Literature Review fulfilled the objective of synthesizing the field's foundations, demonstrating a fundamental paradigm shift from pollution control to resource recovery within the circular economy framework.

The intellectual landscape of Waste Lubricant Oil (WLO) management has fundamentally shifted, evolving from a local pollution problem into a central component of global resource recovery strategies. This evolution is best understood through the integrated lenses of Theory, Context, Characteristics, and Methodology (TCCM), which collectively define the current state of research.

The Theoretical Foundations of the field are strongly rooted in sustainability and systemic thinking. At the macro level, research is guided by principles of the Circular Economy, viewing WLO not as waste but as a valuable secondary resource, reinforcing the need for closed-loop industrial systems. This is supported by Life-Cycle Assessment (LCA), which is used extensively to quantitatively compare the environmental burdens and benefits of different management options (e.g., regeneration vs. energy recovery). Further anchoring the work are the concepts of Industrial Symbiosis (where WLO from one sector becomes a feedstock for another) and Green Chemistry (advocating for cleaner, solvent-

free regeneration processes). For conversion technologies, the theoretical underpinning relies heavily on advanced kinetics, particularly for modelling and optimizing thermo-chemical processes like pyrolysis and hydrocracking.

These theoretical approaches are applied across three critical Contextual Drivers. First, the Heavy Industrial Sector, exemplified by steel processing, provides a major context due to the large volumes of contaminated rolling oils and sludges generated. Second, Energy Recovery remains a significant driver, positioning WLO as a high-potential feedstock for liquid fuel production, often motivated by national energy diversification goals. Third, Environmental Remediation forms a key context, focusing on the detoxification and cleanup of soils and waters contaminated by historical or accidental WLO spills, often driven by strict policy mandates.

The Technological Characteristics of the research reveal five dominant, specialized clusters:

1. Regeneration and Solvent Recovery: This cluster focuses on maximizing the yield and purity of Group I/II base oils, prioritizing techniques like solvent extraction (using green solvents) and membrane filtration to separate contaminants and additives.
2. Thermo-chemical Conversion: This cluster is geared toward producing high-quality liquid fuels via processes such as catalytic pyrolysis and hydrocracking, with a heavy emphasis on kinetics modelling to enhance efficiency and selectivity.
3. Biological Remediation: Utilizing microbial consortia and bioreactors, this area addresses detoxification and contaminant breakdown, focusing on optimizing growth kinetics for effective environmental cleanup.
4. Eco-Friendly Lubricant Development: This forward-looking cluster aims at source reduction by developing bio-based or nano-enhanced lubricants, reducing both toxicity and reliance on petroleum resources.
5. Policy and Life-Cycle Assessment (LCA): This cluster serves an integrative function, providing a macro-level quantitative framework for comparing the overall environmental and economic performance of the other four technological pathways.

Finally, the Methodological Approaches reflect a convergence of empirical testing and computational modelling. Research relies heavily on laboratory-scale experimental validation, utilizing advanced analytical instruments (FTIR, GCMS, ICP) to characterize feedstock and product quality. Crucially, the field is maturing by increasingly incorporating pilot-scale industrial trials to prove scalability. This empirical work is supported by advanced computational techniques such as LCA and Multi-Criteria Decision Analysis (MCDA), which are vital for integrating technical performance data with sustainability metrics and complex decision-making processes.

Reusing waste oil called regeneration is usually the best choice for both the environment and the economy. However, we face problems. For instance, the successful methods developed in research labs are tough to scale up for large factory use. We also need consistent testing methods to properly compare all the different recycling approaches. Importantly, we must better understand the hidden, long-term environmental costs of just burning the oil for energy or mixing it into other products. To solve this, future research must look closely at the costs and practicalities of new technologies to ensure they can actually work in a real-world, industrial setting.

Despite all the research done so far, we still have to put in focused effort to solve these issues. We need serious research into the costs and feasibility of advanced reuse technologies. This is the main challenge in getting them out of the lab and into industrial use. We must also agree on standard methods for testing. This will allow us to accurately compare how good different recycling methods are for both the planet and our wallets.

Most importantly, policies must change. Governments need to go beyond old waste rules and create a mandatory system: reuse (regeneration) must come first before any oil is used for energy. This shift, combined with financial support like Extended Producer Responsibility (EPR) schemes and other incentives, is vital to make the circular economy model happen and save our global resources.

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