

RE-PRO OIL: Conceptual Design of an Integrated Dual-Stage Condensation System for Waste Lubricating Oil Pyrolysis

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ABSTRACT

Keywords:

**Waste lubricating oil
Pyrolysis
Dual-stage
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Waste-to-energy
Circular economy**

The increasing generation of waste lubricating oil (WLO) and the growing demand for sustainable energy have intensified interest in waste-to-energy technologies that support the achievement of Sustainable Development Goal (SDG) 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production). Among available conversion technologies, pyrolysis offers significant potential for recovering valuable hydrocarbon products from WLO; however, existing studies have primarily focused on reactor optimization, catalyst development, and fuel characterization, while limited attention has been given to integrated downstream product separation. This study aimed to develop the RE-PRO OIL (Recovery and Production Oil) conceptual engineering framework for selective fuel-fraction recovery through an integrated dual-stage condensation system. A Systematic Literature Review (SLR) following the PRISMA 2020 guideline and a bibliometric analysis using VOSviewer were conducted on Scopus-indexed publications. From 555 initial records, 200 publications were analyzed bibliometrically and 75 articles were synthesized for engineering development. The analysis identified research hotspots, knowledge gaps, and engineering requirements that were translated into the proposed framework integrating feedstock pretreatment, catalytic upgrading, dual-stage condensation, selective hydrocarbon fraction recovery, gas handling, and future validation. The proposed framework provides a systematic engineering reference for prototype development, selective fuel recovery, and future optimization of WLO pyrolysis systems, thereby supporting sustainable waste-to-energy implementation and circular economy practices.

INTRODUCTION

The accelerating global demand for energy, driven by industrialization, urbanization, and transportation development, continues to increase dependence on fossil fuels while simultaneously generating substantial quantities of hazardous industrial waste. Among these wastes, waste lubricating oil (WLO) represents a critical environmental challenge because of its complex composition, including degraded hydrocarbons, heavy metals, sulfur compounds, nitrogen-containing substances, and residual lubricant additives. Inappropriate disposal practices, such as uncontrolled combustion or direct discharge into soil and water bodies, may cause long-term environmental contamination and ecological degradation. Nevertheless, WLO retains a considerable hydrocarbon content

and calorific value, making it a promising alternative feedstock for waste-to-energy technologies that support resource recovery, circular economy principles, and sustainable energy production (An et al., 2024; Donthu et al., 2021; Felizardo & Carver, 2020; Kusmiyati & Fudholi, 2025).

Among various waste-to-energy technologies, pyrolysis has been widely recognized as one of the most effective thermochemical conversion processes for transforming WLO into valuable products because it decomposes long-chain hydrocarbons under oxygen-limited conditions into liquid hydrocarbons, combustible gases, and solid carbonaceous residues. Numerous studies have demonstrated that catalyst selection, reactor configuration, heating rate, vapor residence time, and reaction temperature significantly influence product distribution and fuel quality. Recent developments have also focused on catalytic upgrading using zeolite-based catalysts to enhance hydrocarbon selectivity and reduce undesirable heavy compounds, thereby improving the potential of pyrolysis-derived fuels as alternative energy resources (Donthu et al., 2021; Mishra et al., 2021; Muhbat et al., 2025; Osei et al., 2021)

Although significant progress has been achieved in WLO pyrolysis, most existing studies primarily emphasize reactor optimization, catalyst development, liquid fuel yield, or fuel characterization. The resulting liquid products are generally reported as mixed pyrolysis oil, while the recovery of specific hydrocarbon fractions based on their boiling-range characteristics receives considerably less attention. Furthermore, condensation systems are commonly regarded as auxiliary cooling units instead of engineering components capable of controlling hydrocarbon fractionation during vapor condensation. Consequently, the integration of feedstock pretreatment, catalytic cracking, and sequential condensation into a unified process architecture remains insufficiently explored. This limitation constitutes a significant research gap because selective recovery of gasoline-like and diesel-like fuel fractions could substantially simplify downstream upgrading while improving process efficiency and product selectivity (Mishra et al., 2021; Muhbat et al., 2025; Osei et al., 2021; Öztürk et al., 2024; Quan et al., 2026)

To systematically examine this research gap, the present study employed a Systematic Literature Review (SLR) following the PRISMA 2020 framework combined with bibliometric analysis. From an initial dataset of 555 publications retrieved from the Scopus database, 200 eligible studies were selected for bibliometric mapping and 75 studies were further synthesized through systematic review after applying predefined inclusion and exclusion criteria. The bibliometric visualization indicates that current research is predominantly concentrated on pyrolysis, waste oil utilization, catalyst

development, biofuel production, and process optimization. In contrast, studies addressing integrated dual-stage condensation, sequential hydrocarbon fractionation, and engineering-oriented fuel-fraction recovery remain relatively scarce. These findings demonstrate that the current research landscape has not yet established a comprehensive engineering framework integrating conversion and selective product separation into a single technological system.

Based on the evidence synthesized through the systematic review and bibliometric mapping, this study introduces RE-PRO OIL (Recovery and Production Oil) as a conceptual engineering framework for an integrated dual-stage condensation system aimed at selective fuel-fraction recovery from waste lubricating oil pyrolysis. Unlike previous studies that separately investigated reactor performance, catalyst optimization, or product characterization, the proposed framework integrates waste lubricating oil pretreatment, oxygen-limited pyrolysis, catalytic upgrading, sequential dual-stage condensation, and product collection into a unified process architecture. The first condensation stage is conceptually designed to recover relatively heavier hydrocarbon fractions, whereas the second stage selectively condenses lighter hydrocarbon fractions according to differences in volatility and boiling-range characteristics. Consequently, the proposed framework shifts the role of the condensation system from a passive cooling unit to an active engineering component governing hydrocarbon fractionation and selective product recovery. This integrated perspective represents the principal scientific contribution of the present study and establishes a technological foundation for future prototype development, process optimization, GC-MS characterization, fuel property evaluation, and environmental assessment.

Finally, this study aims to develop the RE-PRO OIL conceptual engineering framework through systematic evidence synthesized from systematic literature review and bibliometric analysis. The proposed framework is expected to provide scientific guidance for the design of integrated dual-stage condensation systems supporting selective fuel-fraction recovery, waste-to-energy implementation, circular economy practices, and the achievement of Sustainable Development Goal (SDG) 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production).

RESEARCH METHOD

This study employed a qualitative research design based on a **Systematic Literature Review (SLR)** integrated with bibliometric analysis to develop the conceptual engineering framework of **RE-PRO OIL (Recovery and Production Oil)**. Rather than

conducting experimental validation, the study synthesized scientific evidence from previous publications to identify technological trends, engineering requirements, research gaps, and conceptual design considerations for an integrated dual-stage condensation system intended for selective fuel-fraction recovery from waste lubricating oil (WLO) pyrolysis.

This study employed a qualitative research design based on a Systematic Literature Review (SLR) integrated with bibliometric analysis to develop the RE-PRO OIL (Recovery and Production Oil) conceptual engineering framework. Unlike experimental studies that validate process performance through laboratory testing, this research synthesized scientific evidence from previously published studies to establish a comprehensive understanding of current technological developments in waste lubricating oil (WLO) pyrolysis. The combined approach enabled the identification of research trends, technological advancements, catalyst applications, process parameters, product characteristics, and existing research limitations associated with selective fuel-fraction recovery. Consequently, the study focused on generating an evidence-based conceptual framework rather than experimentally evaluating a prototype or optimizing operating conditions.

The research methodology was structured into four sequential stages. First, a **Systematic Literature Review** was conducted to systematically collect, screen, and synthesize relevant publications following the PRISMA 2020 guideline. Second, **bibliometric analysis** was performed using VOSviewer to map publication trends, keyword relationships, and emerging research themes, thereby providing a quantitative overview of the scientific landscape. Third, the findings from both approaches were integrated through **engineering synthesis**, in which engineering-related information including reactor configuration, catalytic upgrading, condensation strategies, and fuel-fraction recovery was comparatively analyzed to identify technological requirements and unresolved research gaps. Finally, these synthesized findings were translated into the **RE-PRO OIL conceptual engineering framework**, representing an integrated dual-stage condensation system for selective recovery of gasoline-like and diesel-like fuel fractions. Therefore, the proposed framework constitutes the primary outcome of this study and serves as a scientific foundation for future prototype development and experimental validation.

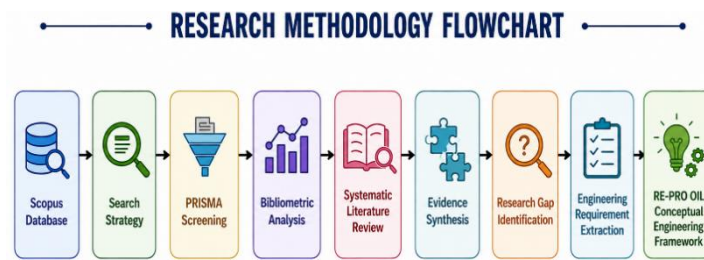


Figure 1. Research methodology for developing the RE-PRO OIL conceptual engineering framework.

Scientific publications were collected exclusively from the Scopus database because it is one of the largest multidisciplinary indexing platforms that provides high-quality, peer-reviewed scientific literature. Scopus was selected to ensure the reliability, consistency, and international visibility of the reviewed publications while minimizing the inclusion of non-peer-reviewed sources. The literature search was limited to English-language journal articles published between 2021 and 2026, representing the most recent developments in waste lubricating oil (WLO) pyrolysis, catalytic upgrading, hydrocarbon recovery, condensation technologies, and waste-to-energy applications. The literature retrieval process employed combinations of keywords representing the principal concepts of this study, including "Waste Lubricating Oil," "Waste Engine Oil," "Pyrolysis," "Catalytic Pyrolysis," "Fuel Recovery," "Dual-Stage Condensation," "Biofuel," and "Waste-to-Energy." Boolean operators (AND and OR) were applied to combine keywords and improve the relevance of the retrieved publications. The search strategy was designed to maximize the identification of studies related to waste lubricating oil conversion, thermochemical processing, catalytic upgrading, hydrocarbon fraction recovery, and integrated fuel production systems. All retrieved records were subsequently exported for screening and bibliometric analysis.

Table 1. Search Strategy Used for Literature Collection

Component	Description
Database	Scopus
Publication Year	2021–2026
Language	English
Document Type	Journal Articles
Keywords	Waste Lubricating Oil; Waste Engine Oil; Pyrolysis; Catalytic Pyrolysis; Fuel Recovery; Dual-Stage Condensation; Biofuel; Waste-to-Energy
Search Operator	Boolean operators (AND, OR)
Bibliometric Software	VOSviewer

The literature search was conducted in May 2026, resulting in an initial dataset of 555 publications indexed in the Scopus database. The retrieved records were systematically screened following the PRISMA 2020 guideline to remove duplicate publications and studies that did not satisfy the predefined inclusion and exclusion criteria. After the screening process, 200 publications were retained for bibliometric analysis to examine publication trends, keyword co-occurrence, and research evolution, while 75 highly relevant studies were selected for systematic literature synthesis. These publications provided the scientific evidence required to identify key technological developments, engineering requirements, and research gaps in waste lubricating oil (WLO) pyrolysis. The findings obtained from the reviewed literature were subsequently used as a basis for formulating the RE-PRO OIL conceptual engineering framework, ensuring that the proposed system was grounded in existing scientific knowledge and relevant research developments.

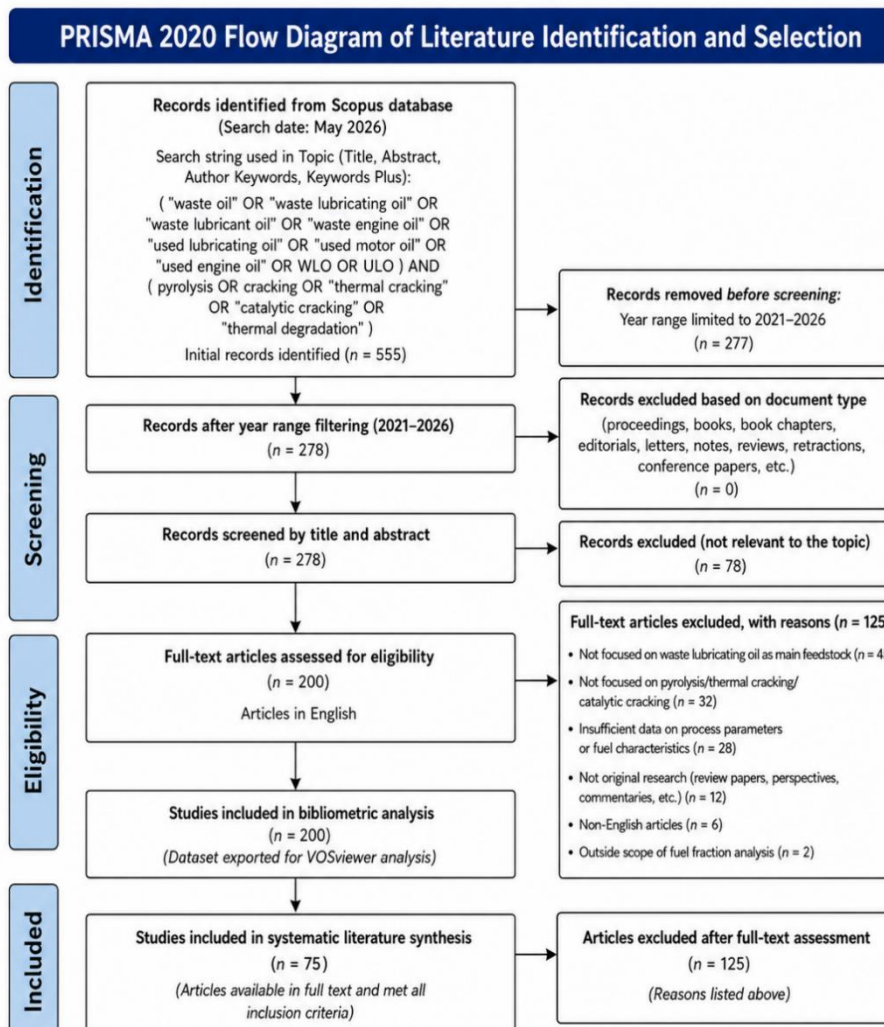


Figure 2. PRISMA 2020 flow diagram of the literature identification and selection process.

To complement the systematic literature review, bibliometric analysis was conducted using VOSviewer (version 1.6.20) to quantitatively map the scientific landscape of waste lubricating oil (WLO) pyrolysis research. This approach complements the systematic literature review by providing an objective overview of publication patterns, research evolution, and relationships among scientific topics that cannot be comprehensively identified through conventional qualitative review alone. Bibliometric analysis enables the identification of dominant research themes, emerging technological developments, and potential knowledge gaps, thereby supporting a more systematic interpretation of the existing literature.

The bibliometric dataset consisted of 200 publications that met the predefined eligibility criteria after the PRISMA screening process. Bibliographic information, including titles, abstracts, author keywords, and citation metadata, was exported from the Scopus database and processed using VOSviewer. The software was employed to construct keyword co-occurrence networks based on author keywords, allowing the visualization of thematic relationships and the identification of major research clusters within the selected literature.

Three complementary visualization techniques were employed to interpret the bibliometric data. Network visualization was used to illustrate relationships among keywords and identify thematic clusters based on co-occurrence frequency. Overlay visualization was applied to examine the temporal evolution of research topics by distinguishing earlier and more recent publication trends. Meanwhile, density visualization was utilized to identify highly investigated topics and research hotspots according to keyword occurrence density. In addition, publication trend analysis was performed to evaluate the annual growth of scientific publications related to WLO pyrolysis during the study period.

The results of the bibliometric analysis were subsequently integrated with the systematic literature synthesis to identify current technological trends, emerging research hotspots, and unresolved research gaps. These findings served as the scientific basis for extracting engineering requirements and developing the RE-PRO OIL conceptual engineering framework, which constitutes the primary outcome of this study.

Following the bibliometric analysis, a systematic literature synthesis was conducted using the 75 selected publications that satisfied all predefined inclusion criteria. Each publication was comprehensively reviewed to extract engineering-related information relevant to waste lubricating oil (WLO) pyrolysis and selective fuel-fraction recovery. Unlike conventional narrative reviews, the synthesis process focused on systematically identifying comparable engineering variables rather than merely summarizing previous

findings. This approach enabled the integration of scientific evidence from multiple studies into a coherent engineering perspective for conceptual framework development. The extracted variables covered the principal technological aspects reported in previous studies, including feedstock characteristics, reactor configuration, operating conditions, catalyst utilization, condensation strategies, product distribution, analytical characterization methods, and reported research limitations. These variables were selected because they directly influence the design and performance of pyrolysis systems and provide essential engineering information for developing an integrated dual-stage condensation system.

Table 2. Engineering Variables Extracted from Previous Studies

Category	Variables Extracted	Purpose of Extraction
Feedstock	Waste lubricating oil characteristics	Feedstock evaluation
Reactor	Reactor configuration and reactor type	Process comparison
Operating Conditions	Temperature, heating rate, vapor residence time	Process optimization
Catalyst	Catalyst type and catalytic function	Catalytic upgrading
Condensation	Condensation strategy and cooling configuration	Fuel-fraction recovery
Product	Product distribution (liquid, gas, char)	Product performance evaluation
Characterization	GC-MS analysis, ASTM fuel properties	Product quality assessment
Reported Limitations	Technical limitations and research recommendations	Research gap identification

The extracted engineering variables were subsequently compared across all selected studies to identify technological similarities, methodological differences, and recurring engineering challenges. Comparative analysis was performed to evaluate how reactor design, catalyst selection, operating parameters, and condensation systems influence hydrocarbon recovery and product characteristics. The synthesis process also enabled the identification of research trends and technological limitations that remain insufficiently addressed in the current literature.

Finally, all extracted variables were systematically categorized and synthesized to generate engineering knowledge rather than isolated research findings. The synthesized evidence served as the basis for identifying engineering requirements and defining the functional architecture of the proposed RE-PRO OIL conceptual engineering framework. Consequently, the systematic literature synthesis not only summarized previous studies

but also translated scientific evidence into engineering design considerations for future prototype development and experimental validation.

The development of the proposed RE-PRO OIL (Recovery and Production Oil) conceptual engineering framework was conducted through a structured synthesis of findings obtained from the systematic literature review (SLR) and bibliometric analysis. Rather than being formulated solely from theoretical assumptions, the framework was developed by integrating scientific evidence from previous studies with engineering design considerations to address existing limitations in waste lubricating oil (WLO) pyrolysis systems.

Initially, bibliographic data retrieved from the Scopus database were systematically screened using the PRISMA approach to ensure that only relevant publications were included in the analysis. The selected literature was subsequently analyzed using VOSviewer to identify publication trends, research themes, and research hotspots within the field of WLO pyrolysis. These analyses provided a comprehensive understanding of the current state of research and the evolution of scientific interest over recent years.

The outputs obtained from the bibliometric analysis were then synthesized to identify research gaps that remain insufficiently explored in the existing literature. Particular attention was given to the limited integration of downstream product separation, selective fuel fraction recovery, gas management, and comprehensive process integration within current WLO pyrolysis systems. These identified knowledge gaps served as the primary basis for defining the engineering aspects required for the development of an integrated conceptual system.

Based on the identified knowledge gaps, an engineering requirements identification process was performed to determine the essential functional components that should be incorporated into the proposed system. The engineering requirements included feedstock pretreatment, catalytic upgrading, dual-stage condensation, selective fuel fraction recovery, gas handling, and provisions for future experimental validation. These requirements were synthesized into a unified conceptual engineering framework that aims to integrate the complete conversion process from feedstock preparation to product recovery.

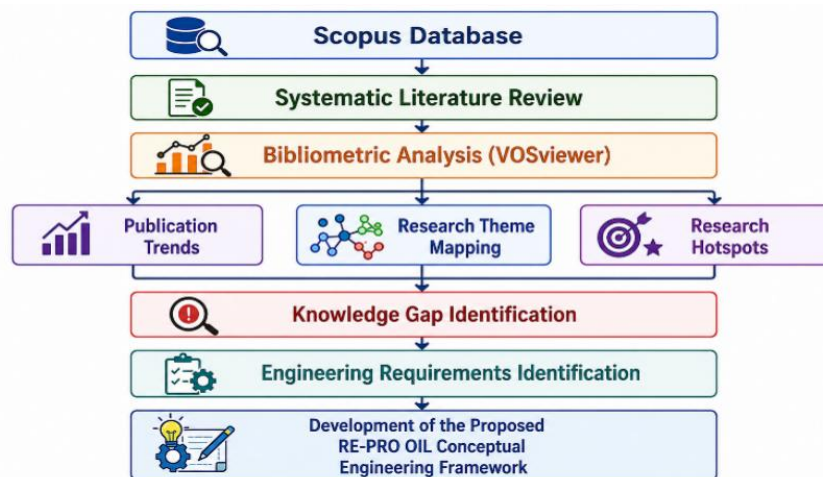


Figure 3. Methodological workflow for developing the proposed RE-PRO OIL conceptual engineering framework.

As illustrated in Figure 3, the framework development process follows a sequential workflow beginning with bibliographic data collection from the Scopus database, followed by systematic literature review and bibliometric analysis. The bibliometric outputs including publication trends, research theme mapping, and research hotspots provide the analytical foundation for identifying knowledge gaps within the current body of literature. These knowledge gaps are subsequently translated into engineering requirements, which are synthesized into the proposed RE-PRO OIL conceptual engineering framework.

RESULTS AND DISCUSSION

The annual publication distribution of the 75 studies selected for systematic literature synthesis is presented in Figure 4. These publications were obtained after the PRISMA screening process and represent the final dataset used for qualitative engineering synthesis. As illustrated in Figure 4, the number of selected publications generally increased during the study period, from 6 publications in 2021 to 28 publications in 2025, indicating a growing scientific interest in waste lubricating oil (WLO) pyrolysis research. Although only 8 publications were included for 2026, this value should be interpreted with caution because the literature search was conducted in May 2026, meaning that the publication year was still incomplete at the time of data collection.

The increasing publication trend reflects the expanding role of WLO pyrolysis in addressing global challenges related to energy transition, circular economy, and sustainable waste management. The increasing demand for alternative liquid fuels, coupled with growing environmental concerns regarding the disposal of hazardous waste lubricating oil, has encouraged researchers to explore thermochemical conversion technologies capable of recovering valuable hydrocarbon products. Consequently, WLO

pyrolysis has evolved from a conventional waste treatment method into a promising waste-to-energy approach that simultaneously contributes to resource recovery and environmental protection.

A noticeable increase in publication activity occurred between 2023 and 2025, suggesting a shift in research emphasis from conventional pyrolysis studies toward process optimization and product quality improvement. Earlier investigations primarily focused on reactor performance and liquid product yield, whereas more recent studies increasingly addressed catalyst development, catalytic upgrading, advanced condensation strategies, and fuel characterization. This evolution indicates that current research is no longer limited to maximizing product quantity but is increasingly directed toward enhancing fuel quality, improving hydrocarbon selectivity, and developing more integrated processing systems.

Despite the steady increase in publication output, the systematic literature synthesis also revealed that most previous studies investigated individual process components independently, such as reactor optimization, catalyst performance, or product characterization. Comparatively fewer studies proposed integrated engineering systems capable of combining catalytic upgrading with sequential dual-stage condensation for selective fuel-fraction recovery. This observation highlights an important research gap and provides the scientific justification for developing the proposed RE-PRO OIL conceptual engineering framework, which integrates pretreatment, catalytic pyrolysis, dual-stage condensation, selective product recovery, and future experimental validation into a unified engineering architecture.

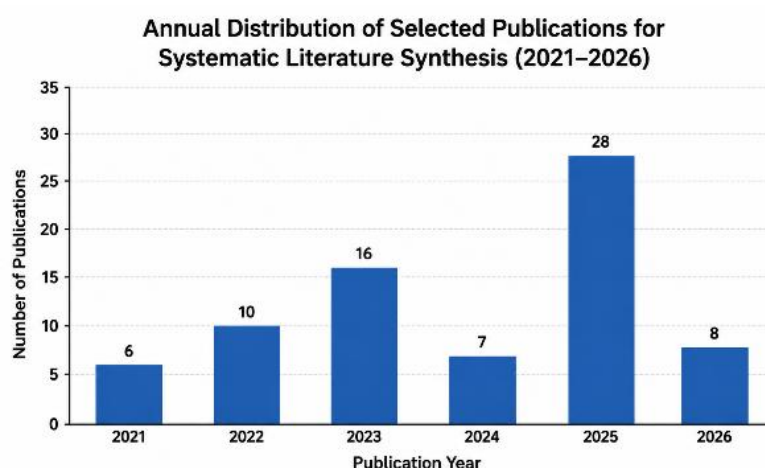


Figure 4. Annual distribution of the 75 publications selected for systematic literature synthesis during the 2021–2026 study period.

To further understand the intellectual structure of waste lubricating oil (WLO) pyrolysis research, a bibliometric keyword co-occurrence analysis was conducted using VOSviewer. The analysis aimed to identify the dominant research themes, examine the relationships among keywords, and investigate the temporal evolution of research interests within the selected literature. In the network visualization, each node represents a keyword, the node size reflects its occurrence frequency, and the connecting lines indicate the strength of co-occurrence between keywords. Different colors in the network visualization represent thematic clusters, whereas the overlay visualization uses the Average Publication Year (APY) to illustrate the relative emergence of research topics over time.

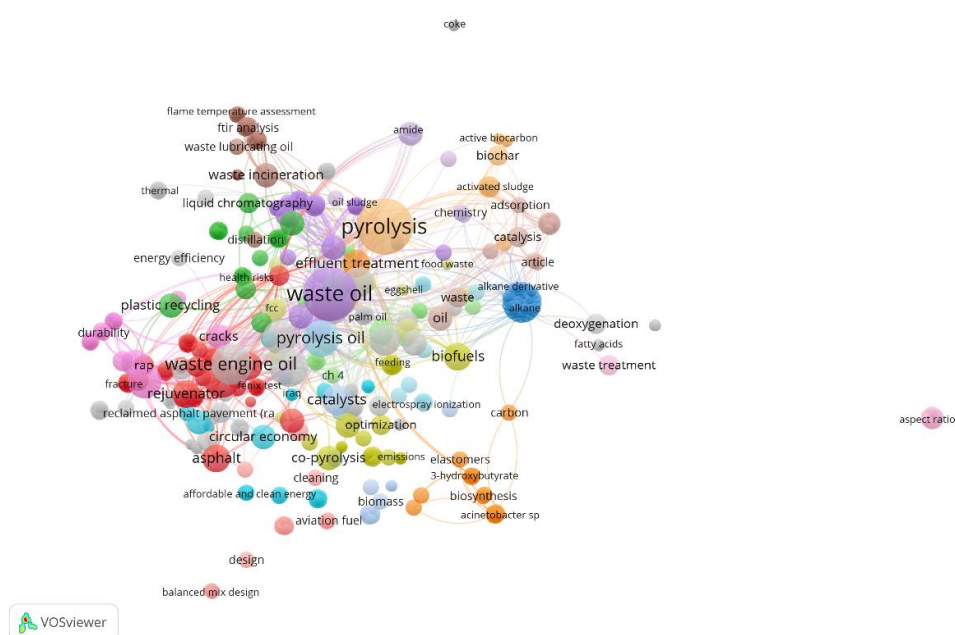


Figure 5. Keyword co-occurrence network of waste lubricating oil pyrolysis research generated using VOSviewer.

The keyword co-occurrence network reveals that pyrolysis and waste oil are the most prominent and highly connected keywords, indicating that thermochemical conversion of waste lubricating oil remains the central focus of current research. These keywords are closely associated with waste engine oil, pyrolysis oil, catalysts, biofuels, co-pyrolysis, effluent treatment, and waste incineration, demonstrating that previous studies have primarily investigated conversion technologies, catalyst-assisted upgrading, fuel production, and environmental management of waste-derived feedstocks.

A second group of closely connected keywords comprises catalysis, optimization, biochar, waste treatment, and related conversion processes. This thematic group reflects

continued efforts to improve reaction efficiency, enhance liquid fuel quality, and increase resource utilization through catalyst development and process optimization.

Another prominent research theme is represented by keywords such as waste engine oil, rejuvenator, asphalt, reclaimed asphalt pavement, and circular economy. These keywords indicate that, besides fuel production, waste lubricating oil has increasingly been explored as a secondary resource for sustainable pavement materials and other circular economy applications. The coexistence of these interconnected themes demonstrates that WLO research has gradually expanded beyond energy recovery toward broader environmental and engineering applications.

Although the network covers a wide range of research topics related to pyrolysis, catalysis, and resource utilization, keywords directly associated with integrated condensation systems, fuel-fraction separation, or selective condensation are not among the dominant nodes. This observation suggests that downstream separation technologies remain relatively underexplored compared with reactor development, catalytic conversion, and product optimization.

To complement the structural relationships identified in the keyword network, an overlay visualization based on the Average Publication Year (APY) was analyzed to identify how research themes have evolved throughout the publication period.

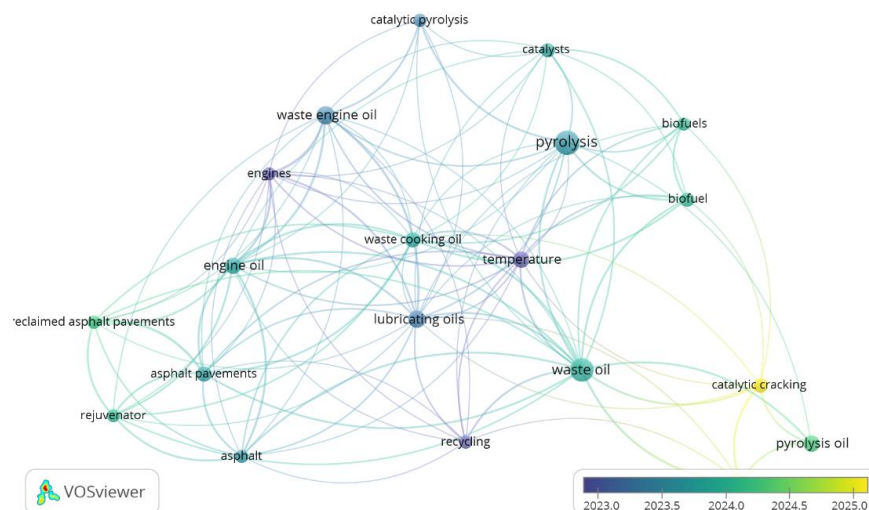


Figure 6. Overlay visualization of keyword co-occurrence based on the Average Publication Year (APY)

The overlay visualization demonstrates a gradual evolution of research themes within the analyzed literature. Keywords displayed in blue to purple, including engines, temperature, lubricating oils, recycling, and catalytic pyrolysis, represent relatively

earlier research topics. These studies primarily focused on feedstock characteristics, operating conditions, and the fundamental aspects of waste lubricating oil conversion. Keywords shown in green, such as pyrolysis, waste oil, engine oil, catalysts, biofuel, and biofuels, indicate themes that became increasingly prominent during the middle stage of the publication period. Their strong interconnections suggest growing research attention toward catalyst-assisted pyrolysis, process optimization, and alternative fuel production. The most recent research themes are represented by yellow-colored keywords, particularly catalytic cracking and pyrolysis oil. Their relatively recent average publication year indicates increasing interest in upgrading liquid products, improving fuel quality, and enhancing hydrocarbon conversion through advanced catalytic processes. Compared with earlier studies that primarily investigated reaction mechanisms and operational parameters, recent publications demonstrate a stronger emphasis on product performance and value-added fuel production.

Overall, the temporal evolution identified through the overlay visualization indicates that WLO pyrolysis research has progressively shifted from fundamental investigations toward catalyst-assisted conversion and product upgrading. Nevertheless, despite the increasing attention given to fuel quality improvement, keywords related to integrated condensation systems, fractional condensation, and selective fuel-fraction recovery remain absent from the dominant research themes. This finding suggests that downstream separation technologies have received relatively limited attention and therefore represent a promising direction for future research. These observations provide a bibliometric foundation for the subsequent identification of research hotspots, knowledge gaps, and engineering requirements that support the development of the proposed RE-PRO OIL Conceptual Engineering Framework.

The bibliometric analyses presented in the previous sections identified the thematic structure and temporal evolution of waste lubricating oil (WLO) pyrolysis research. To further determine the concentration of research activities and identify underexplored areas, a Density Visualization was generated using VOSviewer. Unlike the network and overlay visualizations, the density map highlights the relative intensity of research topics based on keyword occurrence. These findings were subsequently synthesized with the systematic literature review to identify existing knowledge gaps and formulate the engineering requirements for the proposed RE-PRO OIL conceptual framework.

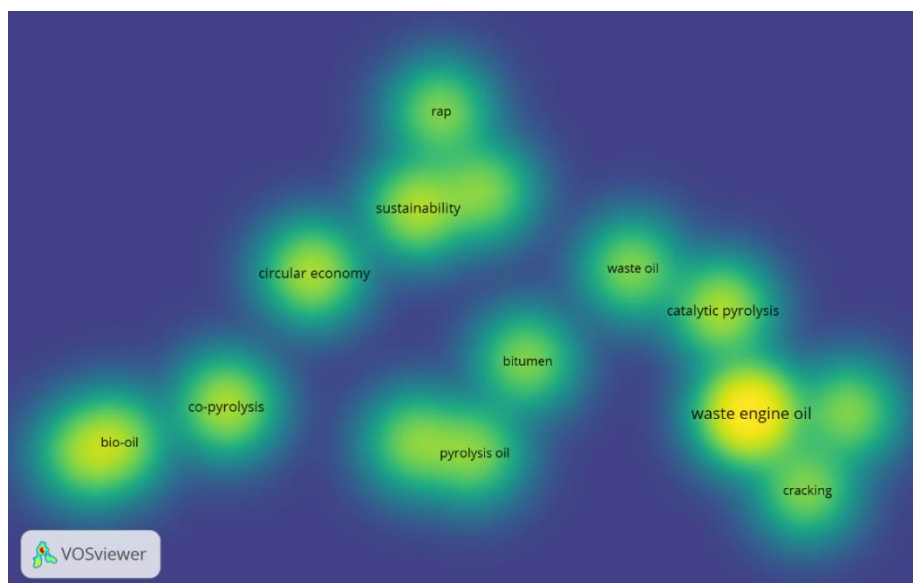


Figure 7. Density visualization of research hotspots in waste lubricating oil pyrolysis research

The density visualization reveals that the highest research intensity is concentrated around the keywords waste engine oil, bio-oil, sustainability, catalytic pyrolysis, pyrolysis oil, circular economy, waste oil, and co-pyrolysis. These highly dense areas indicate that previous studies have primarily focused on converting waste lubricating oil into alternative fuels, improving product quality through catalytic processes, and promoting sustainable waste utilization within a circular economy perspective.

The presence of waste engine oil as the most prominent hotspot demonstrates that the majority of published studies continue to emphasize feedstock utilization and thermochemical conversion. Likewise, the high density of bio-oil and pyrolysis oil indicates sustained interest in maximizing liquid fuel production and improving fuel characteristics. Meanwhile, the prominence of sustainability and circular economy reflects the growing attention toward environmental impact reduction and resource recovery strategies in recent WLO research.

In contrast, keywords associated with integrated condensation systems, dual-stage condensation, selective fuel-fraction recovery, temperature-controlled condensation, pretreatment, and gas handling are absent from the density map. This finding suggests that although considerable progress has been achieved in feedstock conversion and catalytic upgrading, downstream processing technologies for selective product separation remain relatively underexplored. Consequently, these areas represent promising opportunities for future engineering research.

Table 3. Research Gap Analysis in Waste Lubricating Oil Pyrolysis Research

Research Hotspots	Identified Knowledge Gaps	Future Research Direction
Waste engine oil utilization	Limited feedstock pretreatment integration	Integrated pretreatment system
Bio-oil production	Limited selective fuel fraction recovery	Multi-stage fuel separation
Catalytic pyrolysis	Catalytic upgrading and condensation are generally investigated independently	Integration of catalyst and condensation system
Sustainability and circular economy	Limited engineering-oriented process integration	Compact integrated waste-to-energy systems
Pyrolysis oil upgrading	Limited temperature-controlled condensation studies	Dual-stage condensation technology
Co-pyrolysis	Limited utilization of non-condensable gases	Gas handling and energy recovery

The research gap analysis demonstrates that previous studies have predominantly investigated individual processing stages rather than developing integrated engineering systems. Most publications focused on improving feedstock conversion efficiency, catalyst performance, and liquid fuel yield, whereas relatively limited attention has been devoted to downstream product separation and system integration.

Furthermore, although sustainability and circular economy have emerged as important research themes, engineering solutions capable of integrating pretreatment, catalytic upgrading, selective condensation, and gas management into a single operational system remain scarce. This gap indicates that future studies should move beyond reaction optimization toward the development of integrated process configurations capable of improving fuel selectivity and overall system efficiency.

Table 4. Engineering Requirements for RE-PRO OIL Development

Engineering Requirement	Scientific Basis	Function within RE-PRO OIL
Pretreatment unit	Improve feedstock stability by removing moisture and impurities	Enhance process stability before pyrolysis
Catalytic upgrading zone	Improve hydrocarbon cracking and fuel quality	Increase conversion efficiency
Dual-stage condenser	Enable selective condensation at different temperature ranges	Separate diesel-like and gasoline-like fractions
Temperature control system	Maintain stable condensation temperatures	Improve fraction selectivity and process consistency

Gas handling system	Safely manage non-condensable gases	Support environmental protection and future energy recovery
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Based on the identified research hotspots and knowledge gaps, five major engineering requirements were formulated for the conceptual development of the RE-PRO OIL system. First, a pretreatment unit is required to improve feedstock quality by reducing moisture and contaminants prior to pyrolysis. Second, a catalytic upgrading zone is incorporated to enhance hydrocarbon cracking efficiency and improve liquid fuel quality.

A dual-stage condensation system is proposed as the core innovation of the framework to selectively recover diesel-like and gasoline-like fuel fractions using different condensation temperature ranges. To ensure consistent separation performance, a dedicated temperature control system is required to maintain stable thermal gradients throughout the condensation process. Finally, a gas handling system is incorporated to safely manage non-condensable gases while providing opportunities for future energy recovery.

Collectively, these engineering requirements are directly derived from the synthesis of bibliometric findings and systematic literature review results. Therefore, the proposed RE-PRO OIL Conceptual Engineering Framework is positioned as an engineering response to the identified knowledge gaps by integrating pretreatment, catalytic upgrading, selective dual-stage condensation, temperature control, and gas management into a single conceptual waste-to-energy system.

The findings from the bibliometric analysis and systematic literature synthesis indicate that current waste lubricating oil (WLO) pyrolysis research has primarily focused on reactor optimization, catalytic upgrading, and bio-oil production, while comparatively limited attention has been given to integrating downstream separation technologies into a unified engineering system. Based on the identified research hotspots, knowledge gaps, and engineering requirements, this study proposes the RE-PRO OIL (Recovery and Production Oil) conceptual engineering framework, as illustrated in Figure 3. The framework is designed to integrate the entire conversion process from feedstock preparation to selective fuel recovery into a single evidence-based waste-to-energy system.

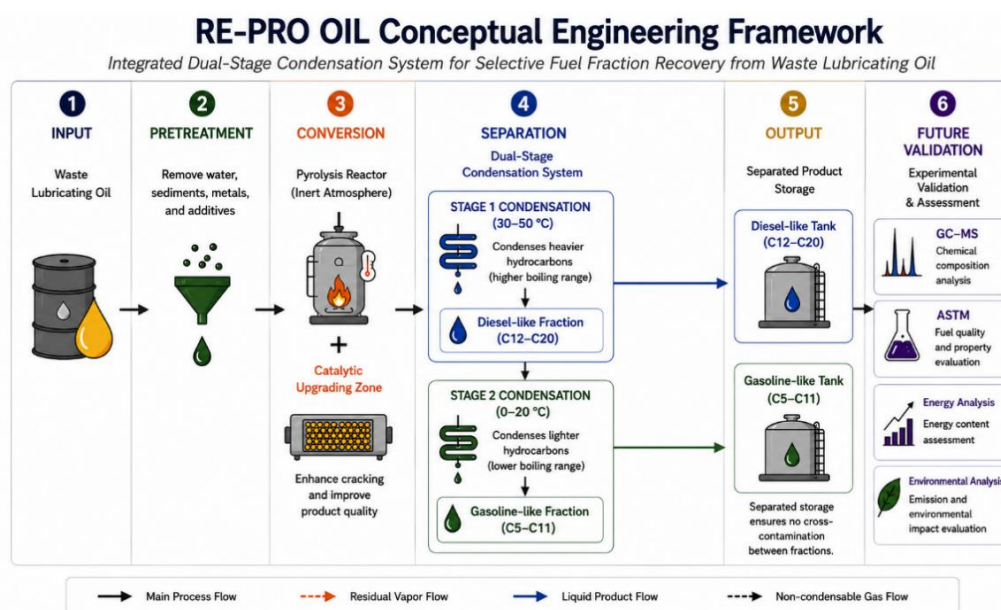


Figure 8. Proposed RE-PRO OIL conceptual engineering framework for integrated selective fuel fraction recovery from waste lubricating oil pyrolysis.

The proposed framework consists of six sequential engineering layers. The first layer comprises the input stage, where waste lubricating oil is introduced as the primary feedstock. Since waste lubricating oil generally contains water, suspended solids, metallic particles, and degraded additives, a pretreatment process is incorporated as the second layer to improve feedstock quality before thermal conversion. This stage is intended to enhance process stability, minimize operational disturbances, and reduce the potential formation of undesirable by-products.

The third layer represents the conversion stage, consisting of a pyrolysis reactor followed by a catalytic upgrading zone. Inside the reactor, waste lubricating oil undergoes thermal cracking at approximately 400–550 °C under an oxygen-limited atmosphere, producing hydrocarbon vapors. These vapors subsequently pass through a catalytic upgrading unit, where secondary cracking reactions promote the formation of lighter hydrocarbons and improve the overall quality and selectivity of the liquid fuel products. This integrated conversion approach was formulated based on the literature synthesis, which consistently highlights the importance of catalytic upgrading in enhancing pyrolysis performance.

The fourth layer constitutes the principal innovation of the proposed framework, namely the dual-stage condensation system. Unlike conventional single-stage condensers, the proposed configuration employs two condensation zones operating at different temperature ranges. The first condensation stage (30–50 °C) preferentially condenses heavier hydrocarbon compounds, producing a diesel-like fraction (C12–C20). The

remaining vapors are subsequently directed to the second condensation stage (0–20 °C), where lighter hydrocarbons are condensed to produce a gasoline-like fraction (C5–C11). This sequential condensation strategy is expected to improve product selectivity while minimizing the need for additional downstream refining processes.

Non-condensable gases generated after the second condensation stage are transferred to a dedicated gas handling system, where particulate impurities are removed through gas filtration before the gases are safely discharged or utilized for future energy recovery. Incorporating this unit not only enhances operational safety but also supports more sustainable utilization of residual process energy.

The recovered liquid products are subsequently stored separately in dedicated diesel-like and gasoline-like storage tanks to prevent cross-contamination between fuel fractions. Finally, the framework incorporates a future experimental validation layer, which outlines the analytical methods required to verify the proposed system. Product composition is intended to be evaluated using gas chromatography–mass spectrometry (GC–MS), fuel quality will be assessed according to relevant ASTM standards, while additional energy and environmental analyses will be conducted to evaluate overall system performance and sustainability.

Overall, the proposed RE-PRO OIL framework represents an integrated engineering approach derived from the synthesis of bibliometric findings and systematic literature review. Rather than optimizing individual process units independently, the framework combines pretreatment, catalytic upgrading, selective dual-stage condensation, gas management, and product validation into a unified conceptual system. This integration directly addresses the knowledge gaps identified in the previous sections, particularly the limited research on downstream product separation and process integration. Therefore, the proposed framework provides a scientific and engineering foundation for the future development and experimental validation of an integrated waste lubricating oil pyrolysis system.

3.5 Engineering Design Rationale and Future Development

The proposed RE-PRO OIL conceptual engineering framework was developed as an integrated process configuration to address the research gaps identified through the systematic literature review and bibliometric analysis. Previous studies have predominantly focused on individual aspects of waste lubricating oil (WLO) pyrolysis, such as reactor design, catalyst performance, or product yield optimization, whereas relatively limited attention has been given to integrating pretreatment, catalytic upgrading, selective condensation, and downstream product management into a single engineering system. Consequently, the proposed framework adopts a holistic process

integration approach in which each processing stage is designed to complement the subsequent stage, thereby supporting more systematic product recovery and facilitating future experimental implementation.

A key engineering feature of the proposed framework is the implementation of a dual-stage condensation system. Conventional WLO pyrolysis systems generally employ a single condenser that recovers a broad mixture of condensable hydrocarbons with a wide boiling-point distribution. In contrast, the proposed configuration utilizes two sequential condensation stages to promote the preferential condensation of hydrocarbon compounds with different volatilities. This staged approach is expected to improve product selectivity and simplify downstream separation by reducing the overlap between heavier and lighter hydrocarbon fractions. Although the effectiveness of this configuration requires experimental verification, the concept provides a rational engineering strategy for enhancing selective fuel recovery in integrated WLO pyrolysis systems.

The proposed operating temperatures of 30–50 °C for the first condensation stage and 0–20 °C for the second stage were selected based on the general boiling characteristics of hydrocarbon compounds commonly reported in WLO pyrolysis and petroleum fractionation literature. The higher-temperature condenser is intended to preferentially recover heavier condensable hydrocarbons, while the lower-temperature condenser is designed to collect lighter compounds that remain in the vapor stream after the first condensation stage. These temperature ranges are therefore proposed as conceptual engineering design parameters rather than optimized operating conditions, and further experimental studies are required to determine their influence on condensation efficiency, product selectivity, and overall system performance.

The incorporation of a catalytic upgrading stage before the condensation unit constitutes another important engineering consideration. Catalytic upgrading has been widely reported to promote secondary cracking reactions, reduce the molecular weight of heavy hydrocarbons, and improve the distribution of lighter liquid products. Integrating this stage upstream of the dual-stage condenser is therefore expected to produce a vapor composition that is more suitable for selective fraction recovery. Within the proposed framework, the recovered liquid products are classified as diesel-like (C12–C20) and gasoline-like (C5–C11) fractions based on their typical carbon-number ranges and corresponding boiling-point characteristics. These classifications are intended solely as engineering references for conceptual process design and do not imply that the recovered products satisfy commercial fuel specifications or applicable fuel quality standards. Comprehensive characterization remains necessary before any conclusions regarding fuel quality or practical application can be established.

Future research should focus on validating the proposed conceptual framework through prototype fabrication and controlled laboratory experiments. Experimental verification should include the construction of an integrated WLO pyrolysis system incorporating catalytic upgrading and dual-stage condensation, followed by gas chromatography-mass spectrometry (GC-MS) analysis to determine the chemical composition of the recovered liquid fractions. In addition, fuel properties should be evaluated according to relevant ASTM testing standards to assess their physicochemical characteristics and determine their suitability for potential fuel applications.

Beyond product characterization, future investigations should also evaluate the overall engineering performance of the proposed system through energy efficiency assessment, including thermal efficiency, product recovery efficiency, and energy distribution throughout the conversion process. Furthermore, environmental assessment, such as emissions analysis and waste reduction potential, is required to determine the sustainability benefits of the proposed system within a waste-to-energy framework. Following successful laboratory-scale validation, the conceptual framework may provide a foundation for pilot-scale development and process scale-up, including optimization of operating parameters, integration of non-condensable gas utilization, and assessment of long-term operational performance for practical implementation in waste lubricating oil recovery systems.

CONCLUSION

This study developed the RE-PRO OIL (Recovery and Production Oil) conceptual engineering framework through the integration of a systematic literature review and bibliometric analysis of waste lubricating oil (WLO) pyrolysis research. The bibliometric results revealed that recent studies have primarily concentrated on reactor development, catalytic upgrading, and bio-oil production, while comparatively limited attention has been devoted to downstream product separation and process integration. Based on the identified research hotspots, knowledge gaps, and engineering requirements, the proposed framework integrates feedstock pretreatment, catalytic upgrading, dual-stage condensation, selective fuel fraction recovery, gas handling, and product storage into a unified conceptual engineering system. This framework provides a structured engineering approach for improving process integration and selective recovery of hydrocarbon fractions in WLO pyrolysis systems, while serving as a scientific reference for future waste-to-energy technology development.

Although the proposed framework has not yet been experimentally validated, it establishes a systematic basis for future engineering implementation and optimization. Subsequent studies should focus on prototype fabrication, experimental verification of the proposed dual-stage condensation system, chemical characterization of the recovered

products using gas chromatography-mass spectrometry (GC-MS), evaluation of fuel properties according to relevant ASTM standards, and assessment of energy efficiency and environmental performance. Furthermore, future research should investigate operating parameter optimization, utilization of non-condensable gases, and pilot-scale scale-up to evaluate the technical feasibility and practical applicability of the proposed RE-PRO OIL framework.

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