FEEDSTOCK EFFECTS, CATALYST PERFORMANCE AND PROCESS OPTIMIZATION IN WASTE PLASTIC-TO-FUEL PYROLYSIS: A REVIEW

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ABSTRACT

The rapid accumulation of plastic waste and the growing demand for alternative energy sources have intensified interest in thermochemical conversion technologies capable of recovering value from end-of-life plastics. Among these technologies, thermal and catalytic pyrolysis have emerged as promising approaches for converting waste plastics into liquid fuels with properties comparable to conventional petroleum-derived fuels. This review examines recent advances (2019–2025) in waste plastic pyrolysis, with particular emphasis on the influence of feedstock characteristics, catalyst performance, and operating conditions on liquid fuel yield and quality. The review evaluates the pyrolytic behaviour of major plastic feedstocks, including polypropylene (PP), polyethylene (PE), polystyrene (PS), polyethylene terephthalate (PET), and mixed plastic wastes. Polyolefins and polystyrene consistently demonstrate superior liquid fuel yields, whereas PET and PVC present processing challenges due to the formation of oxygenated and chlorinated compounds. The role of catalysts, particularly zeolite-based materials such as ZSM-5 and HZSM-5, is assessed with respect to reaction temperature reduction, hydrocarbon selectivity, and fuel upgrading. The effects of key process parameters, including temperature, residence time, and reactor configuration, are also discussed. Findings indicate that catalytic pyrolysis generally achieves higher liquid yields, improved selectivity towards gasoline-range hydrocarbons, and lower energy requirements than thermal pyrolysis. Furthermore, the produced oils exhibit calorific values ranging from 41–49 MJ/kg and possess physicochemical properties that enable blending with conventional transportation fuels. Despite these advantages, challenges related to feedstock heterogeneity, catalyst deactivation, product upgrading, and economic viability continue to hinder large-scale deployment. The review highlights current trends and identifies opportunities for improving process efficiency and fuel quality, thereby supporting the development of sustainable waste plastic-to-fuel technologies within a circular economy framework.

Keywords: Plastic waste, Thermal pyrolysis, Liquid fuel, Catalysts, Catalytic pyrolysis, Feedstock characteristics

1 INTRODUCTION

The world's energy consumption is projected to 580 million tera joules of which fossil fuels accounts for 83% of the energy used in 2022 [1]. The main driver of climate change leading to global warming is the combustion of fossil fuels, which releases harmful gases into the atmosphere, recently the world has been burning approximately 1000 barrels of fossil fuel per second [2]. However, the reliance on fossil fuels has led to significant environmental challenges, including greenhouse gas emissions, air pollution, and climate change [2]. The combustion of fossil fuels releases harmful gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), contributing to global warming and extreme weather events [3]. If the global temperature increases by 2^{o}C, millions of people are expected to suffer fatal consequences [3]. The tension between environmental concerns and the need for economic growth will intensify in the coming three decades [4]. These nonbiodegradable materials, if not properly disposed of, can cause significant harm to the environment. Furthermore, their open burning contributes to air pollution [5]. Plastic waste constitutes one of the most pervasive environmental pollutants of the modern era. Global plastic production exceeded 400 million tonnes in 2023 and is projected to double by 2050, with only approximately 9% of all plastic ever produced having been recycled [6]. The remaining fraction accumulates in landfills, contaminates oceans and terrestrial ecosystems, or is openly incinerated, releasing toxic pollutants into the atmosphere. Conventional mechanical recycling, while important, is severely limited in scope i.e., it is largely inapplicable to contaminated, mixed, or multi-layer plastic streams, which constitute the majority of post-consumer waste. This has created an urgent need for complementary chemical recycling technologies capable of handling heterogeneous, real-world waste streams. Pyrolysis, defined as the thermochemical decomposition of organic materials at elevated temperatures in the absence of oxygen, has emerged as one of the most technically promising of these approaches. Unlike incineration, which merely destroys the chemical energy embodied in plastic polymers, pyrolysis recovers this energy in the form of condensable liquid oil, non-condensable gases, and a solid char residue. The liquid fraction, in particular, has physicochemical properties closely analogous to conventional petroleum fractions, positioning it as a potential "drop-in" fuel or chemical feedstock [7, 8]. The process can be conducted under purely thermal conditions or enhanced through the use of catalysts, the latter offering significant advantages in terms of reduced operating temperatures, improved product selectivity, and higher liquid yields. Despite considerable scientific progress, the pathway from laboratory demonstration to viable commercial operation remains fraught with challenges, including feedstock variability, catalyst deactivation, and the need for cost-effective post-processing to meet transportation fuel specifications. This work presents a structured review of recent progresses (2019-2025) in thermal and catalytic pyrolysis for plastic waste into liquid fuels, investigating how different processing conditions affect the properties of the produced liquid fuels. Our objective is to offer a combined view of current progress, identify well established trends, and outline key challenges that must be addressed to move this technology toward commercial use.

2 METHODOLOGY

This review synthesizes research and review articles from 2019 to 2025. Literature was identified through systematic searches of major academic databases, including Scopus and Google Scholar using keyword combinations such as "plastic pyrolysis," "catalytic pyrolysis liquid fuel," "waste plastic thermochemical conversion," and "pyrolysis oil fuel properties." Only peer-reviewed journal articles, conference proceedings, and published theses falling within the 2019–2025 publication window were considered for inclusion. Studies were excluded if they (i) did not report quantitative yield or fuel quality data, (ii) focused exclusively on gasification or hydrothermal liquefaction without a pyrolysis component, or (iii) lacked clear specification of feedstock type or operating conditions. The selected studies were evaluated by comparing four central factors: the type of waste plastic used (PP, PE, PS, PET, and mixed waste), catalyst employed (zeolites, clays, metal oxides, or composite materials), operating temperature, and the resulting outputs (oil yield, fuel quality, and hydrocarbon composition). Data extraction was performed using a standardized template capturing feedstock composition, catalyst identity and loading, reactor type, temperature range, residence time, liquid oil yield (wt%), and reported fuel properties. The methodology comprised three phases as shown in Figure 1.

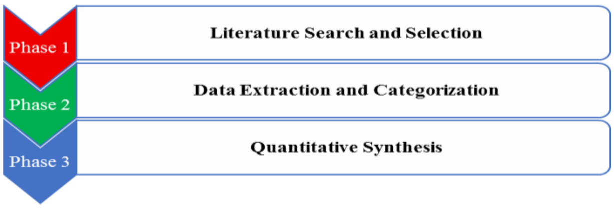

Figure 1. Outline of the applied methodology

3 RESULTS AND DISCUSSION

The analysis of the selected papers confirms and quantifies the intensification of scientific interest in the catalytic pyrolysis of plastic waste to liquid fuel and chemical production. A total of 62 primary research articles and 14 review articles published between 2019 and 2025 were included in this synthesis after screening against the eligibility criteria described in the methodology. The temporal distribution of the corpus reveals a marked acceleration in publication rate from 2022 onwards, consistent with growing regulatory pressure on plastic waste management and renewed interest in waste-to-energy solutions. Geographically, the reviewed literature spans contributions from South and Southeast Asia, East Asia, the Middle East, Africa, and Europe, indicating that research interest in plastic pyrolysis is now truly global. The gathered data highlights a significant shift toward catalytic processes, with over 70% of experimental studies employing a catalyst to enhance the liquid yield, quality, quantity and save energy. The papers were categorized and analysed based on four primary variables. i) Feedstock Type (PP, PE, PS, PET, Mixed plastics), ii) Catalyst Type (zeolites, clays, metal oxides, composites), iii) Reaction temperature, iv) Key findings (liquid yield, fuel properties, hydrocarbon distribution).

3.1 Influence of Feedstock on Pyrolysis liquid oil yield and composition

The plastic type is the primary determinant of pyrolysis liquid oil yield and composition due to differences in polymer structure and degradation mechanisms. The Influence of feedstock on pyrolysis liquid oil yield and composition gathered from literature is shown in Figure 2.

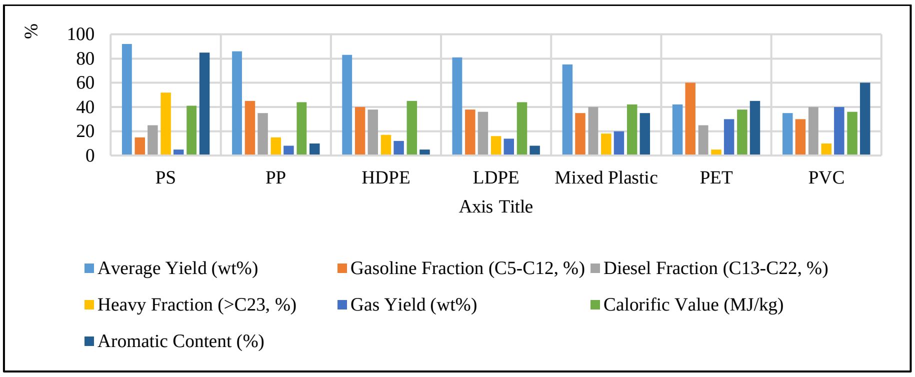

Figure 2. Influence of Feedstock on Pyrolysis liquid oil yield and composition

Polyolefins (HDPE, LDPE, PP) are a class of thermoplastic polymers derived from simple olefins (alkenes) as monomers, primarily consisting of carbon and hydrogen atoms. They are the most widely produced and used plastics globally [9]. These are the most studied and effective feedstocks for liquid fuel production. Their purely hydrocarbon structure yields liquid oil with high calorific value and minimal oxygenates. Liquid yields for polyolefins are consistently high, often between 70-95 wt% under optimal catalytic conditions [10, 11]. PP and HDPE tend to produce a broad hydrocarbon range (C5-C24), suitable for gasoline, kerosene, and diesel fractions. Polystyrene (PS) is a synthetic aromatic polymer made from the monomer styrene, known for its rigidity, transparency, and versatility. It is one of the most widely used plastics globally, particularly in packaging and insulation [12]. PS pyrolysis typically yields the highest liquid quantities, often >90 wt%, even at lower temperatures, due to its readily cleavable backbone [6, 12]. However, PS-derived oil is rich in aromatic compounds which can be valuable as chemical feedstocks but may lead to higher engine emissions if used directly as fuel. Polyethylene terephthalate (PET) and polyvinyl chloride (PVC) are considered challenging feedstocks. PET contains oxygen, leading to oxygenated compounds and lower oil yields (8-40 wt%). PVC contains chlorine, which produces corrosive HCl gas and contaminates the oil, requiring pre -treatment or sophisticated catalysts for dichlorination [13, 14]. Catalytic co-pyrolysis with polyolefins is a common strategy to improve the processing of these materials [15]. Table 1 presents the yield of these feedstocks.

Table 1. Liquid fuel yields by primary feedstock type

Feedstock	Liquid Yield (wt%)	Key findings	Author
Polypropylene (PP)	70-90	Broad hydrocarbon range (C5-C24), high olefin content initially	[16, 17]
Polyethylene (HDPE/LDPE)	75-95	Aliphatic hydrocarbons, high calorific value (45 MJ/kg)	[9, 11]
Polystyrene (PS)	85-96	Aromatic-rich (styrene, ethylbenzene), high yield	[12, 18]
Mixed Plastics	60-85	Variable composition depending on mixing ratio (may require upgrading)	[19, 20]
PET	8-45	Contains oxygenates, yield improves significantly with co-pyrolysis	[21]

3.2 Catalyst

Catalyst is a substance that increases the rate of a chemical reaction without itself being consumed or permanently altered in the process. Catalysts are essential in shifting pyrolysis from a simple thermal cracking process to a targeted fuel production technology [22]. Some of the most commonly used catalysts identified in literature as discussed below.

Zeolites (ZSM-5, HY, HZSM-5, FCC): The most widely used catalyst class. Their microporous structure and tunable acidity (Bronsted and Lewis acid sites) promote carbon-carbon bond scission (cracking), isomerization, and aromatization. ZSM-5 is exceptionally effective for producing high-octane gasoline-range hydrocarbons (C5-C12) [10, 23]. FCC catalysts are noted for promoting mono-olefin formation [24].

Natural Clays and Minerals (Bentonite, Kaolin): Cost effective and widely available, these catalysts offer moderate acidity and are effective for bulk cracking, often increasing liquid yield and reducing wax formation [25, 26]. Their performance however is generally lower than that of synthetic zeolites.

Metal-Loaded and Composite Catalysts: Impregnating supports (zeolites, alumina, biochar) with metals (Ni, Co, Cu, Ga) adds functionalities like dehydrogenation, hydrogen transfer, and deoxygenation. These can tailor product streams, for example, Ni-based catalysts favor syngas/H_2 production [27], while Ga/ZSM-5 increases aromatic yield [28]. Bimetallic and single-atom alloy catalysts (Ru_1Co) show promise for high selectivity at lower temperatures [29].

3.2.1 Catalytic impact on process parameters

Worldwide findings indicate that catalysts significantly lower the effective pyrolysis temperature by 50–150°C compared to purely thermal processes [23, 30] Correspondingly, catalysts reduce the activation energy, as demonstrated by a study where ZSM-5 lowered it from 323 kJ/mol to 164 kJ/mol for HDPE [16]. Beyond temperature reduction, catalysts exert a profound mechanistic influence on the pyrolysis reaction pathway. In thermal pyrolysis, polymer chain scission occurs primarily via random free-radical mechanisms, producing a broad and unpredictable distribution of hydrocarbon fragments. Catalysts with Brønsted and Lewis acid sites, particularly zeolites, redirect this process toward a more controlled carbocation-mediated mechanism, favouring β-scission reactions that produce shorter-chain, gasoline-range hydrocarbons (C5–C12), while simultaneously suppressing the formation of heavy wax residues characteristic of uncatalyzed processes [24]. The shape selectivity of microporous zeolite frameworks further constrains product distribution, enhancing selectivity for valuable fuel fractions. Furthermore, the presence of a catalyst substantially reduces coke deposition on reactor walls, improving heat transfer efficiency and extending the operational life of reactor components. These combined mechanistic advantages explain why catalytic pyrolysis consistently outperforms thermal pyrolysis on virtually every metric of process performance and product quality [22, 30].

3.3 Optimization of Process Parameters

The optimization of critical process parameters specifically reaction temperature, catalyst-to-feedstock ratio, and residence time constitutes a fundamental lever for enhancing liquid hydrocarbon yield, directing product selectivity toward desirable fuel fractions, and improving the overall energy efficiency of the pyrolysis process.

3.3.1 Temperature

Temperature is the most critical operational parameter, liquid yield typically increases with temperature to an optimum point (450-550°C for thermal, 300-450°C for catalytic), after which secondary cracking promotes non-condensable gas formation, reducing liquid yield [19, 31]. The catalytic pyrolysis of polyolefins (PP and PE) enables a significant reduction in the median operating temperature by 100-125°C compared to thermal processes while also narrowing the interquartile range, demonstrating enhanced process control and energy efficiency, as evidenced by the compiled statistical analysis of temperature data from the reviewed literature [11, 20, 23]. Figure 3 shows the operating temperature comparison for thermal catalytic pyrolysis of waste plastics

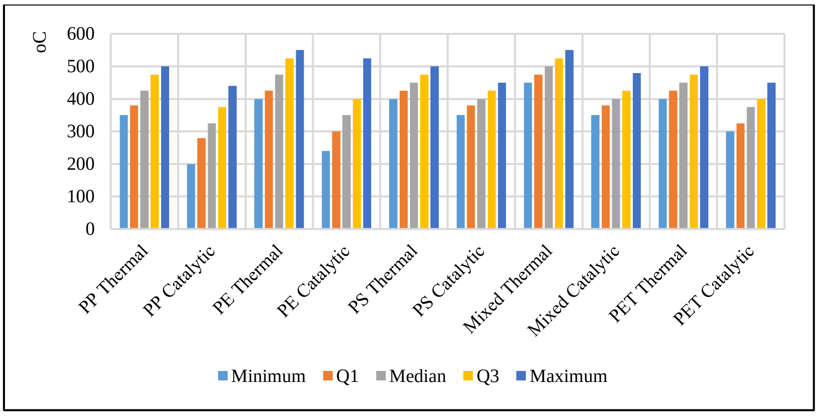

Figure 3. Operating temperature comparison for thermal catalytic pyrolysis of waste plastics

3.3.2 Residence time

Residence time, the duration of vapor-phase reaction, is a pivotal parameter controlling the trade-off between primary cracking and secondary decomposition in plastic pyrolysis. Insufficient time leads to incomplete conversion and waxy products, while excessive time promotes over cracking to gases. Catalysis significantly reduces the optimal residence time from 45-90 minutes (thermal) to 30-45 minutes by accelerating cracking kinetics and directing selectivity toward fuel-range hydrocarbons. This reduction enhances reactor throughput and represents key process intensification for economic feasibility [32]. In thermal pyrolysis, a residence time of 30 minutes represents the kinetic optimum, maximizing liquid yield at 70 wt% with a concurrent gas yield of 25 wt%; shorter durations (≤20 min) lead to incomplete depolymerization and higher gas fractions, while extended times (≥60 min) promote secondary cracking reactions that gradually increase gasoline selectivity at the expense of both total liquid yield and diesel-range hydrocarbons. Figure 4 shows the residence time for thermal pyrolysis.

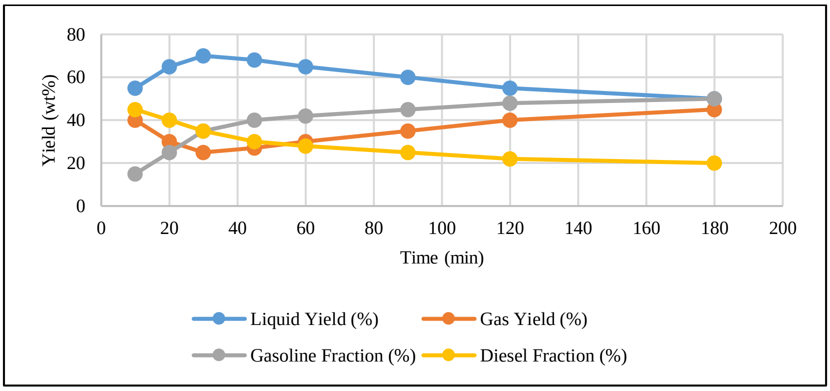

Figure 4. Residence time for thermal pyrolysis

For catalytic pyrolysis, the liquid yield peaks sharply at 88 wt% with a residence time of 30 minutes, while simultaneously minimizing gas production to 8 wt% and enabling a tunable product slate where extending time to 45 minutes further increases the gasoline fraction to 70% at only a minor yield cost. Figure 5 shows the residence time for catalytic pyrolysis.

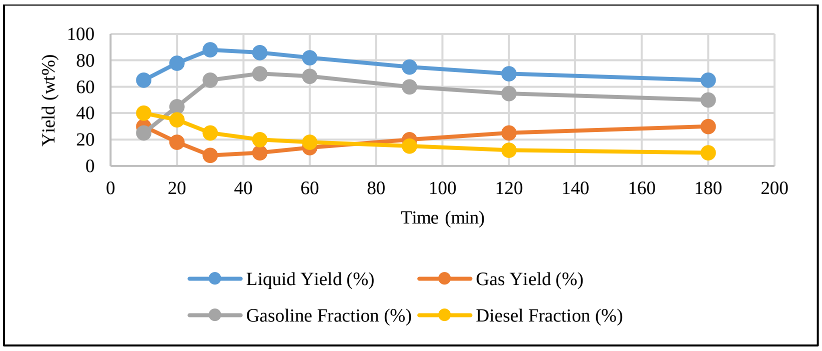

Figure 5. Residence time for catalytic pyrolysis

3.3.3 Reactor design and mode

Studies employ batch, semi-batch, fixed-bed, and fluidized-bed reactors. Continuous or two-stage reactor designs (Thermal and catalytic pyrolysis) show superior performance for controlling product slate and managing catalyst life [33, 34].

3.4 Fuel Properties and Engine Compatibility

The ultimate test of pyrolysis liquid fuel is its suitability as a fuel. Oils from polyolefins often have calorific values of 40-49 MJ/kg exceeding that of commercial diesel with calorific values of 45 MJ/kg [9]. Density, viscosity, and flash point frequently fall within the ranges for diesel or gasoline, especially after simple distillation [35, 36] as shown in Table 2. Direct use of crude plastic liquid fuel in engines faces challenges due to residual olefins, aromatics, or contaminants. Therefore, blending with standard diesel (20/80 or 50/50) is a common and successful strategy to achieve compatible fuel properties [37, 38]. For higher-quality fuels, post-pyrolysis hydro processing is highly effective producing hydrocarbons with >95% similarity to commercial diesel [20, 39]. Table 3 shows the engine performance assessment of plastic-derived fuel blends. Engine tests indicate that plastic-derived fuels can achieve comparable torque and power to conventional fuels. A frequent issue, however, is the trade-off in emissions while CO and unburned hydrocarbons can be comparable or lower with optimized blends, NOx emissions are often higher due to elevated combustion temperatures and aromatic content [7, 40]. Table 4 shows the emission characteristics and mitigation strategies for plastic derived fuels.

Table 2. Physical and chemical properties of liquid fuel obtain from waste plastic

Property	Pyrolysis Oil	Commercial Diesel	Commercial Gasoline	Acceptable Range	Standard Test	Author
Calorific Value (MJ/kg)	41-49	45	44	>40	ASTM D240	[9, 16, 41]
Density (kg/m³)	780-860	820-845	720-780	770-850	ASTM D4052	[8, 9, 42]
Viscosity at 40°C (cSt)	2.5-4.5	2.0-4.5	0.6-0.8	1.9-4.1	ASTM D445	[9, 43, 44] improved oil quality
Flash Point (°C)	38-65	>52	-43 to -40	>55 (diesel)	ASTM D93	[8, 45]
Pour Point (°C)	-15 to -5	-15 to -5	-40 to -60	Below ambient	ASTM D97	[8, 9]
Cetane Number	43-58	48-52	-	>47	ASTM D613	[26, 42]
Octane Number (RON)	85-100	-	87-93	>87	ASTM D2699	[46, 10, 47]
Sulfur Content (ppm)	<50	<10	<10	<10	ASTM D4294	[20, 41, 48]
Water Content (% vol)	0.1-0.5	0.02	0.02	<0.05	ASTM D2709	[30, 45]
Ash Content (% wt)	0.01-0.05	0.01	0.01	<0.01	ASTM D482	[49, 50]

Table 3. Engine performance assessment of plastic-derived fuel blends

Blend Ratio	Engine Type	Power Output	Thermal Efficiency	Specific Fuel Consumption	Limitations	Author
B10 (10% PO)	CI Engine	98-100%	96-98%	1.96	Minor injector deposits	[37, 38, 51]
B20 (20% PO)	CI Engine	95-98%	93-96%	4.92	Higher NOx (+8-12%)	[26, 38, 40]
B50 (50% PO)	CI Engine	90-94%	85-90%	9.85	Cold start issues	[8, 37]
100% PO	Modified CI	85-90%	80-85%	14.75	Fuel system modifications	[14, 26]
G10 (10% PO)	SI Engine	97-99%	95-97%	2.95	Octane boost beneficial	[46, 47]
G20 (20% PO)	SI Engine	94-97%	90-94%	5.9	Valve deposits	[10, 47]

Table 4. Emission characteristics and mitigation strategies for plastic derived fuels

Emission Type	Pyrolysis Oil	Cause	Mitigation Strategy	Author
CO (%)	-20 to +30%	Incomplete combustion	Blend optimization	[38, 40, 51]
HC (ppm)	-15 to +25%	Cold combustion zones	Preheat fuel	[38, 40, 51]
NOx (%)	+10 to +25%	Higher flame temperature	EGR, retarded injection	[7, 40]
Smoke/PM	-5 to +15%	Aromatic content	Additives, blending	[40, 52, 53]
CO_2 (%)	-5 to -15%	Renewable carbon	Life cycle benefit	[54, 55]
PAHs	+20 to +50%	Aromatic structure	Hydro-processing	[14, 56, 57]

3.5 Techno-Economic and Sustainability Considerations

The economic viability of plastic to fuel pyrolysis is scale dependent. Techno-economic analyses indicate that large-scale plants (>50 kM/year) are more likely to be profitable, with returns sensitive to feedstock cost, oil price, and catalyst lifetime [58, 59]. Life Cycle Assessments suggest the process can reduce reliance on fossil fuels and mitigate landfill issues, though net greenhouse gas emissions require careful analysis of the entire energy system [54]. The COVID-19 pandemic in 2020 caused a sharp, temporary pivot from experimental optimization (30%) to desk-based economic and environmental analysis (48%), after which the field reorganized with optimization re-establishing dominance (43% by 2025), additive research demonstrating the most significant sustained growth (8% to 19%), and pretreatment remaining a persistent, unsolved challenge (steady 20%). Figure 6 shows the evolution of Research Focus in Plastic Pyrolysis Literature.

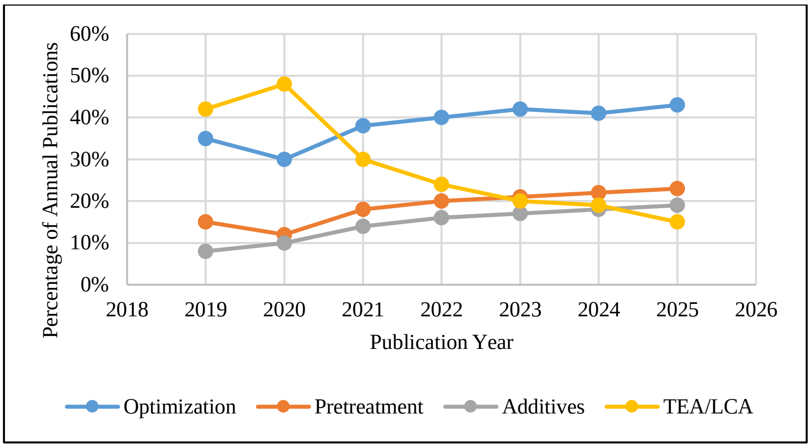

Figure 6. Evolution of research focus in plastic pyrolysis literature (2019-2025)

4 CONCLUSIONS

Catalytic pyrolysis stands as a technologically feasible and promising route for transforming waste plastics into liquid fuels. This review confirms that zeolite-based catalytic systems, operating at moderated temperatures of 300–500°C, can efficiently convert polyolefin-rich waste streams into hydrocarbon mixtures closely resembling conventional transportation fuels. The success of this technology in contributing to a circular economy will depend not just on chemical process optimization, but on overcoming systemic challenges related to feedstock logistics, catalyst economics, and the integration of upgrading processes to produce specification-grade fuels. With continued innovation in catalyst design and process engineering, catalytic pyrolysis can play a substantial role in mitigating the global plastic waste crisis while recovering valuable energy resources. Furthermore, the widespread deployment of plastic-to-fuel pyrolysis technology will require harmonized regulatory frameworks, standardized fuel quality specifications for pyrolysis-derived products, and mechanisms to ensure consistent feedstock supply chains. Life cycle assessments consistently indicate that catalytic pyrolysis of mixed plastic waste yields net greenhouse gas savings relative to incineration and landfilling, provided that the energy inputs to the process are sourced from low-carbon electricity. Future research should prioritize the development of regenerable, poison-tolerant catalysts capable of maintaining performance over extended operational cycles with real-world heterogeneous feedstocks, the design of continuous and modular reactor systems that can be economically scaled to match regional waste volumes, and the integration of pyrolysis with complementary processes such as hydroprocessing and distillation to produce fuels fully conforming to ASTM or EN standards. As the global community intensifies its commitment to plastic waste reduction and circular economy principles, catalytic pyrolysis offers a technologically credible, energetically favourable, and environmentally beneficial route to transform what is currently a waste liability into a valuable energy resource.

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