

Review Paper

Catalytic Pyrolysis of Plastic Waste for Gasoline Fuel: Reaction Mechanism Engine Integration

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Abstract

The escalating accumulation of plastic waste demands not only scalable but integrative conversion solutions. Among thermochemical routes, catalytic pyrolysis has emerged as a promising pathway to produce gasoline-range hydrocarbons from plastic polymers compatible with spark-ignition engines. This review critically evaluates recent advancements in pyrolysis of key plastics polypropylene (PP), polyethylene (PE), polystyrene (PS), polyethylene terephthalate (PET), and polyvinyl chloride (PVC) with a focus on fuel yield, hydrocarbon distribution, and engine-level performance. Comparative analysis reveals PP as the most viable feedstock, achieving up to 85% liquid yield and producing oil with high Research Octane Numbers (RON 85–95), outperforming PE and PS in combustion efficiency and emission compliance. However, persistent challenges such as fuel instability, catalyst deactivation, and elevated aromatic emissions particularly from PS complicate real-world deployment. The review further dissects the interplay between catalyst type, reactor design, and post-treatment, highlighting how these variables modulate product quality and engine operability. Notably, 10–20% PP/PE-derived pyrolysis gasoline blends demonstrate near-parity with conventional gasoline in Brake Thermal Efficiency and regulated emissions, without requiring engine modifications. This work bridges molecular-level reaction chemistry with combustion diagnostics and policy-aligned emission metrics, offering a rare multiscale synthesis. By articulating process-emission-performance trade-offs, it provides a strategic reference for researchers and practitioners aiming to scale waste-to-fuel systems within circular economy frameworks.

Keywords: Catalytic pyrolysis; Plastic-derived gasoline; Polypropylene; Octane rating; Engine emissions; Waste valorization; Circular economy

1. Introduction

1.1. Urgency of the Problem

The unchecked accumulation of plastic waste has evolved into a planetary-scale crisis, burdening both terrestrial and marine ecosystems with persistent pollutants that resist natural degradation due to plastics' complex chemical structure and the presence of hazardous additives [1], [2]. Traditional end-of-life treatments such as

landfilling and incineration are increasingly impractical, constrained by limited capacity, energy intensity, and secondary pollution risks [3]. This escalating waste burden not only threatens environmental integrity but also signals a critical need for technological interventions that can repurpose plastic waste into value-added products particularly fuels while aligning with sustainable resource management frameworks [4].



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1.2. State of the Art

Among thermochemical strategies, pyrolysis especially in its catalytic form has emerged as a scalable and energy-efficient method for converting plastic polymers into liquid hydrocarbons with fuel potential [2], [5]. Unlike mechanical recycling, which suffers from input material restrictions and product downgrading, catalytic pyrolysis tolerates feedstock heterogeneity and generates liquid fractions known as pyrolysis oil, rich in gasoline-range compounds [6]. Advances in catalyst design, particularly the use of zeolites such as HZSM-5, have enhanced the yield and quality of these fuels, enabling closer alignment with commercial gasoline in terms of chemical structure and energy content [7], [8]. Empirical studies also indicate that co-processing strategies such as blending plastic pyrolysis oil with biodiesel or high-octane alcohols can modulate fuel properties to improve combustion efficiency and reduce regulated emissions in spark-ignition and diesel engines [9], [10], [11].

1.3. Knowledge Gap

Despite these advances, the existing body of research remains fragmented, often siloed between catalyst optimization, reaction engineering, and combustion evaluation. Most studies focus narrowly on process efficiency or feedstock performance without connecting upstream conversion chemistry to downstream engine operability. Consequently, essential trade-offs such as yield versus fuel quality, or aromatic content versus emissions compliance are rarely examined holistically. Moreover, critical real-world factors like fuel aging, material compatibility, emission norm conformity, and long-term combustion stability under dynamic engine conditions are substantially underexplored. The lack of integrative analyses linking catalytic mechanisms, product characterization, and engine response represents a core deficiency in the current literature.

1.4. Review Objectives

This review addresses these limitations by offering a multi-scale synthesis that spans from the molecular breakdown of plastic polymers through catalytic pyrolysis to the practical

performance of the resulting gasoline-range fuels in Otto cycle engines. It systematically examines key plastic feedstocks namely polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and polyvinyl chloride (PVC) in relation to catalytic selectivity, product yield, and engine-level metrics such as Brake Thermal Efficiency and emissions. Through critical comparison and synthesis, this work identifies optimal feedstock-catalyst-reactor configurations, assesses practical blending thresholds with conventional fuels, and highlights systemic trade-offs. The novelty lies in bridging chemical reactivity with mechanical performance while revealing regulatory and operational bottlenecks that must be addressed to enable real-world deployment. In doing so, this review positions pyrolysis gasoline not merely as a waste reduction strategy, but as a viable candidate for decarbonizing transport fuels within circular economy paradigms.

2. Methods

This systematic review was conducted in strict accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines, ensuring both procedural transparency and reproducibility. The primary objective was to synthesize the catalytic pyrolysis of plastic waste into gasoline-range fuels with a downstream application focus on Otto-cycle engines. The methodology was designed not merely to aggregate findings but to bridge multidisciplinary insights across reaction chemistry, fuel properties, and combustion performance.

2.1. Literature Search Strategy

A comprehensive literature search was executed across three major databases Scopus, ScienceDirect, and Web of Science utilizing Boolean combinations of keywords and operators such as ("*catalytic pyrolysis*" AND "*plastic waste*" AND "*gasoline*" AND "*engine performance*"). Filters were applied to include only peer-reviewed publications from 2011 to 2025, written in English. The initial pool yielded 126 records. Following the removal of duplicates ($n = 8$), 118 unique records were screened for eligibility based on title and abstract.

2.2. Inclusion and Exclusion Criteria

The inclusion criteria were deliberately stringent to ensure the review's applicability to both chemical and mechanical domains. Studies were retained if they reported (i) catalytic or thermal pyrolysis of plastics, (ii) quantifiable fuel properties (e.g., hydrocarbon composition, RON, yield), and (iii) performance or emission testing on internal combustion engines. Exclusion criteria eliminated papers focused solely on biomass, rubber, or tire pyrolysis, non-English language articles, and those lacking access to full text or offering only abstract-level insights.

Out of the 118 records screened based on title and abstract, 22 were excluded for not aligning with the study's scope 12 addressed pyrolysis pathways unrelated to the research focus, while 10 did not report performance or emission parameters. The remaining 96 articles were subjected to full-text evaluation. During this stage, an additional 17 studies were excluded due to various reasons: four full texts were inaccessible, six lacked sufficient data, two were not published in English, and two were limited to abstract-only content. Consequently, 57 studies met the inclusion criteria and were incorporated into the qualitative synthesis. This final selection comprised 55 peer-reviewed journal articles and two conference proceedings, all of which reported on engine performance trials.

2.3. Quality Assessment

To assess study quality and risk of bias, a three-tiered evaluation matrix was applied. Each study was scored based on (i) methodological rigor (experimental design, replication, and control), (ii) relevance to the pyrolysis-fuel-engine continuum, and (iii) data transparency (availability of yield, emissions, or engine parameters). Only studies scoring $\geq 70\%$ across these criteria were retained for synthesis. This ensured the final dataset comprised high-quality, directly comparable evidence across domains.

2.4. Data Extraction and Thematic Coding

Data extraction followed a structured coding framework capturing:

- Feedstock attributes: PE, PP, PS, PET, PVC, or mixed
- Pyrolysis configuration: thermal vs. catalytic; batch, fluidized-bed, fixed-bed

- Catalyst identity and loading: HZSM-5, FCC, doped zeolites, etc.
- Operational variables: temperature, residence time, feed ratio
- Fuel properties: yield, RON, boiling range, composition (aliphatic/aromatic)
- Engine performance: Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), power output
- Emission metrics: CO, HC, NO_x, particulate matter (if available)

Additionally, techno-economic indicators and life cycle analysis (LCA) results were recorded where available. A synthesis matrix was then used to score and compare the relationships among feedstock–catalyst–reactor combinations and their downstream combustion outcomes.

2.5. Bibliometric and Quantitative Mapping

To enhance analytical depth, a bibliometric analysis was conducted using VOSviewer and Biblioshiny (R package) to generate co-authorship maps, keyword co-occurrence networks, and publication trends. This step provided additional insight into dominant research clusters, emergent topics, and temporal research distribution across the field. Author and citation network analysis further revealed key contributors and methodological hubs shaping this research area.

2.6. PRISMA Flow Diagram

A detailed PRISMA flow diagram ([Figure 1](#)) presents the stepwise selection of studies, showing records identified, screened, excluded, and synthesized. A comprehensive summary categorizes the 57 included studies based on: feedstock type, catalyst used, Engine type tested, journal impact factor, publication year and reported performance/emission outcomes.

This comprehensive narrative presentation enhances traceability, promotes transparency, and enables comparative interpretation of the findings. The PRISMA flow diagram detailing the selection process is provided in [Figure 1](#) to maintain procedural accountability.

3. Results and Discussion

3.1. Novel Contribution and Thematic Integration

This review distinguishes itself from prior works by systematically bridging the upstream

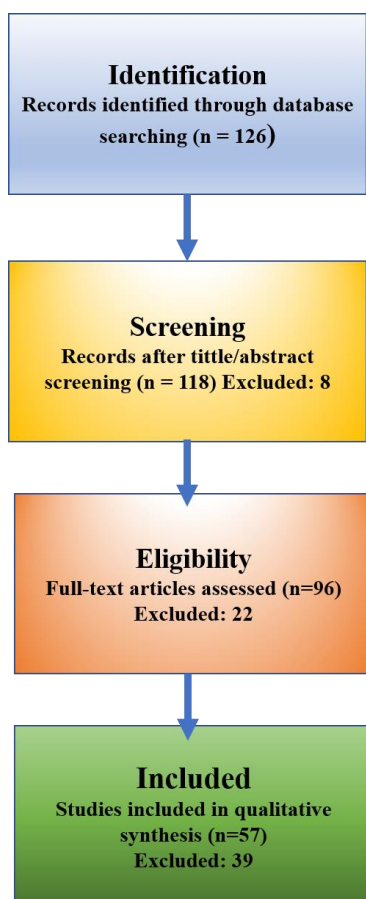


Figure 1. PRISMA flow diagram

pyrolysis reaction mechanisms with downstream engine performance and emissions, a connection often overlooked in earlier studies that tend to isolate either chemical conversion or engine behavior. By synthesizing data across feedstock types, catalyst characteristics, reactor configurations, and real-world combustion outcomes, this work offers an integrative framework to assess the practical viability of plastic-derived gasoline. Importantly, it introduces the concepts of “practical blending ceiling” and “catalyst-engine compatibility” to operationalize system-wide decision-making.

3.2. Feedstock-catalyst Synergy and Performance Determinants

While most studies isolate the impact of feedstock or catalyst, this review emphasizes the synergistic effect of both variables and their downstream influence on product quality. Among the thermoplastics examined, polypropylene (PP) consistently outperforms others in terms of gasoline-range yield and combustion attributes, particularly when

catalyzed with HZSM-5. The RON values between 85–95 achieved from PP are on par with commercial fuels, which is a result of its favorable aliphatic content and cracking kinetics. This makes PP an optimal candidate for minimal-engine-modification fuels [12], [13]. In contrast, polystyrene (PS) presents a performance paradox. Its aromatic-rich pyrolysis oil achieves high octane numbers but leads to combustion instability and elevated emissions, especially under high engine loads. The low H/C ratio, combined with heavy molecular compounds, makes PS-derived oils less compatible with unmodified engines. This dichotomy calls for either advanced upgrading or restriction to controlled co-blending. Polyethylene (PE) generates a wider hydrocarbon distribution, predominantly aliphatic, but offers less selectivity for gasoline-range fractions. While it can serve as a useful co-feedstock, PE-derived oils often require distillation or chemical upgrading to meet fuel-grade specifications. PET and PVC, as expected, remain categorically unsuitable for pyrolysis gasoline. Their degradation releases oxygenated and halogenated compounds, compromising both fuel quality and operational safety. PET’s acidic derivatives and PVC’s HCl emissions cause corrosion, catalyst fouling, and regulatory noncompliance [14], [15]. **Table 1** offers a strategic decision matrix, linking each plastic type with its thermal behavior, emission profile, and post-processing needs. Unlike conventional reviews that treat feedstock characteristics descriptively, this synthesis couples chemical potential with system-wide fuel design implications. Catalyst behavior further complicates this matrix. Zeolite catalysts like HZSM-5 promote high selectivity toward gasoline-range aromatics but may require downstream treatment for emission control. In contrast, FCC catalysts offer broader hydrocarbon yields and improved coke resistance, making them suitable for scale-up. Natural clays offer cost benefits but fall short in selectivity and activity, limiting their industrial applicability. Moreover, operational parameters such as pyrolysis temperature and residence time are rarely optimized in tandem with feedstock-catalyst pairing. The fluidized-bed reactor, for instance, shows superior thermal transfer and homogeneity, which aligns well with PP and

Table 1. Performance and suitability assessment of plastic feedstocks for pyrolysis-based gasoline production

Plastic Type	Pyrolysis Temp (°C)	Liquid Yield (%)	Gasoline Fraction (C5–C12)	RON Potential	Emission Risk	Overall Suitability	Refs.
PE	450–500	60–80	Moderate	Moderate	Low	Medium	[14], [16], [17], [18]
PP	450–500	65–85	High	High (85–95)	Low	Very High	[12], [19], [20]
PS	400–500	60–75	Low	Very High	Moderate–High	Conditional	[21], [22], [23]
PET	500–600	< 50	Very Low	Low	High (acidic)	Not Recommended	[24], [25], [26]
PVC	300–500	< 40	Not Significant	N/A	Very High (Cl)	Hazardous	[3], [27], [28], [29]
Mixed (PE+PP+PS)	450–550	60–75	Moderate–High	Moderate	Moderate	Promising w/ Control	[12], [30], [31], [32]

mixed plastic streams. However, extended residence times risk excessive cracking and coke formation [33], [34]. Thus, PP emerges not merely as a high-yielding feedstock, but as one that aligns favorably with catalytic pathways, reactor dynamics, and final fuel compatibility underscoring its strategic value in future pyrolysis systems.

Figure 2 does more than confirm polypropylene's dominance it maps the strategic trade space between yield and gasoline-range selectivity that fundamentally shapes process economics and product viability. While PP delivers the highest combined score, PE's relatively broad yield with lower C5–C12 concentration suggests higher downstream refining needs, potentially offsetting its production volume advantage. PS, positioned with moderate yield but disproportionately high C5–C12 content, exemplifies a case of quality-over-quantity with inherent combustion trade-offs due to its aromatic intensity. In contrast, PET and PVC occupy the low-value quadrant, reinforcing their technical and regulatory unsuitability. This visual clearly segments feedstocks into performance tiers PP as primary candidate, PE and PS as conditional with treatment, and PET/PVC as exclusionary offering a rapid assessment framework for pyrolysis system design, especially in resource-constrained settings or when targeting specific fuel outputs.

3.3. Chemical Characterization via GC-MS and FTIR

To enrich the understanding of product composition and catalyst selectivity, detailed GC-

MS and FTIR data from the literature were synthesized per catalyst and feedstock. These spectral analyses are indispensable for tracing hydrocarbon chain distributions, identifying functional group transformations, and mapping the catalytic fingerprints of each system. For HZSM-5, the GC-MS spectrum of PP-derived pyrolysis oil is dominated by iso-paraffins (e.g., 2-methylpentane, 3-methylhexane) and monoaromatics such as toluene and xylenes, accounting for over 65% of the total ion count in the C5–C12 range [12], [13], [23]. This pattern underscores the shape-selective cracking facilitated by the zeolite's narrow pore architecture and strong Brønsted acidity. FTIR spectra corroborate these findings with sharp peaks at 2954–2850 cm⁻¹ corresponding to C–H stretching of alkanes, and a moderate band near 1600 cm⁻¹ indicative of aromatic C=C stretching, confirming significant aromatic formation without excessive oxygenates. FCC catalysts, particularly when regenerated from refinery units, yield a more complex GC-MS fingerprint. PP+PE co-feeds processed with FCC typically show broader hydrocarbon classes, including linear alkanes (e.g., n-heptane, n-nonane), branched alkenes, and cyclic hydrocarbons [6], [19], [35]. These products span C6–C20, with a relatively even distribution across gasoline, kerosene, and diesel-range fractions. FTIR results for FCC-treated oils show broader C–H stretching regions and less pronounced aromatic peaks, with additional signals at 1375 cm⁻¹ and 1460 cm⁻¹ corresponding to methyl and methylene group bending suggesting aliphatic dominance. In contrast, PS-derived oils exhibit high aromatic

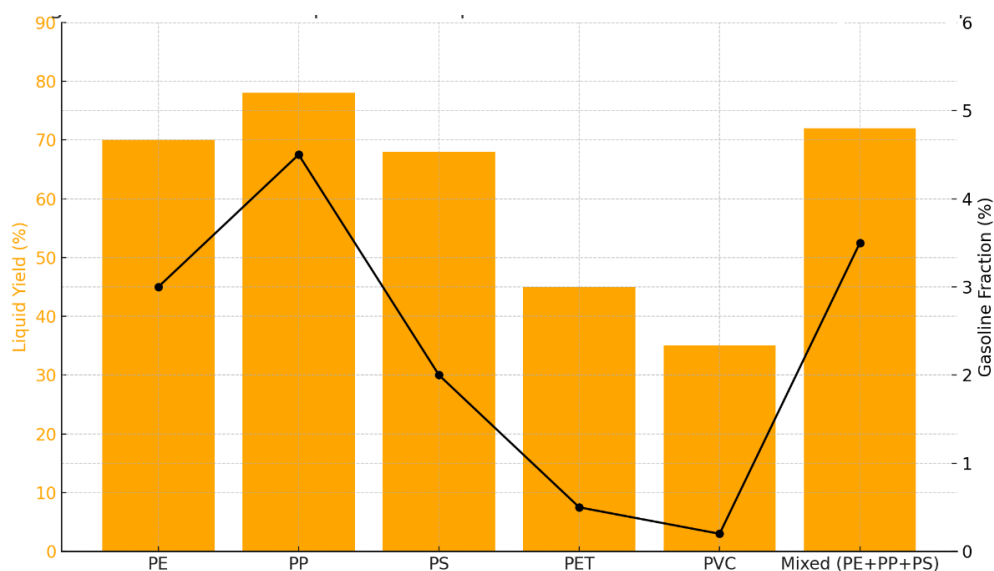


Figure 2. Evaluative comparison of liquid yield and gasoline fraction by plastic type

intensity regardless of catalyst, but especially when processed with HZSM-5. GC-MS analysis frequently reveals benzene derivatives, styrene, and polycyclic aromatics such as indene and naphthalene [21], [23]. FTIR signatures include intense aromatic C=C stretching bands (1600–1580 cm^{-1}) and overtone regions at 2000–1700 cm^{-1} , consistent with polyaromatic structures. The presence of minor phenolic compounds (~2–5% peak area) in some cases hints at partial oxidation or secondary condensation pathways [26]. Clay-based catalysts generate pyrolysis oils with lower aromatic content and higher heavy hydrocarbons (>C15), as revealed by their GC-MS spectra. These oils are characterized by unselective cracking patterns, resulting in waxy aliphatic chains and unresolved complex mixtures (UCMs), particularly in the diesel range. FTIR profiles lack prominent aromatic bands but exhibit wide aliphatic C–H stretches and low-intensity carbonyl peaks, indicating minor oxygenated residues possibly due to insufficient cracking and dehydrogenation efficiency [3], [36]. The summarized GC-MS and FTIR comparisons reveal distinct catalytic pathways: zeolites enhance aromaticity and RON but risk combustion instability; FCC balances aliphatic and aromatic content with broader fractionation; clays underperform in selectivity. These spectral diagnostics reinforce the process-product-performance linkages critical for catalyst selection and fuel design.

Furthermore, a comparative interpretation of dominant compound distributions across catalysts reveals distinct catalytic signatures. Pyrolysis oil catalyzed by HZSM-5 predominantly contains light monoaromatics and iso-paraffins (e.g., toluene, xylene, 2-methylpentane) due to its high Brønsted acidity and narrow pore geometry favoring β -scission and isomerization pathways [12], [23]. FCC-catalyzed oil displays a broader compositional profile with linear alkanes (n-heptane, n-nonane), branched alkenes, and light cycloalkanes, indicating less shape selectivity but enhanced thermal stability [6], [19], [35]. Clay-catalyzed oils exhibit a predominance of long-chain aliphatic hydrocarbons (>C15), characterized by unresolved complex mixtures (UCMs), suggesting insufficient cracking activity and poor molecular discrimination [3], [36]. FTIR spectra reinforce this differentiation: zeolites yield strong aromatic C=C bands (~1600 cm^{-1}), FCC oils present mixed aliphatic/aromatic features, and clays show dominant aliphatic C–H stretches (~2850–2950 cm^{-1}) with residual carbonyls (~1710 cm^{-1}). These compound-specific distributions substantiate the performance of zeolites in maximizing gasoline-range aromatics, FCC in balancing fractionation, and clays as low-activity supports. Hence, compound dominance correlates directly with catalyst pore architecture, acid site density, and reaction pathway facilitation critical for tailoring fuel selectivity and downstream combustion behavior.

Furthermore, the implications of dominant compound profiles in pyrolysis oil extend beyond chemical classification they fundamentally dictate how these fuels interact with combustion systems and emission regulations. For instance, pyrolysis oils rich in iso-paraffins and monoaromatics, typically derived from PP via HZSM-5 catalysis, exhibit high volatility, favorable vaporization, and smooth flame propagation in spark-ignition engines. These molecular features correlate with improved Brake Thermal Efficiency (BTE) and reduced CO and HC emissions due to complete oxidation, particularly at low to moderate blending ratios [12], [13], [23]. Conversely, PS-derived oils, characterized by high concentrations of benzene, styrene, and other polyaromatic hydrocarbons (PAHs), tend to impair ignition stability and promote incomplete combustion. This leads to higher Brake Specific Fuel Consumption (BSFC), combustion knocking, and elevated emissions of unburned hydrocarbons, carbon monoxide, and nitrogen oxides, all of which threaten regulatory compliance [21], [23], [28]. The compound profile thus serves as a predictive proxy for engine performance: lighter, aliphatic-rich fractions enhance efficiency and emissions control, while heavier aromatics, although octane-boosting, may necessitate advanced engine calibration or post-treatment systems. Therefore, aligning pyrolysis fuel design with target compound distribution is crucial for optimizing both mechanical output and environmental conformity.

3.4. Catalyst Type, Composition, Thermal Stability, Deactivation, and Cost-Performance Analysis

The selection and behavior of catalysts are pivotal in dictating the efficiency, selectivity, and scalability of catalytic pyrolysis for plastic waste valorization. Among the catalysts investigated in the literature, zeolites particularly HZSM-5 emerge as the most widely studied and industrially relevant due to their high acidity, shape selectivity, and well-defined pore structure. HZSM-5 promotes the formation of gasoline-range aromatic hydrocarbons through strong Brønsted acid sites and a high Si/Al ratio, which facilitates the cracking of long-chain polymers into light olefins and aromatics [12], [13], [14]. However, this aromatic dominance can pose

combustion and emission challenges, necessitating careful consideration of downstream upgrading or co-blending strategies. In contrast, Fluid Catalytic Cracking (FCC) catalysts often derived from spent industrial units exhibit broader hydrocarbon product distributions and are more coke-resistant under extended pyrolysis conditions. Their hierarchical pore networks and moderate acidity favor aliphatic hydrocarbon production and reduce secondary cracking to gaseous fractions [6]. This makes FCC catalysts advantageous for mixed plastic feedstocks, where compositional heterogeneity may otherwise suppress yield selectivity. Natural clays and modified silicates have also been explored due to their low cost and environmental benignity. However, their poor thermal stability and low acid site density significantly limit their catalytic activity, resulting in reduced gasoline-range selectivity and increased char formation [3], [36]. Their primary utility may lie in pre-treatment stages or as catalyst supports rather than stand-alone active phases.

In addition to traditional zeolites and FCC catalysts, recent investigations have expanded the catalytic repertoire to include modified zeolites, clay-based materials, and metal-doped systems that offer unique performance characteristics. Modified zeolites such as HZSM-11 and USY exhibit altered pore geometries and acid site distributions that tailor product selectivity toward branched aliphatics and monoaromatics, often yielding higher RON values with improved thermal stability [23], [37]. Clays while generally limited by low acidity can be structurally activated or doped with transition metals to enhance cracking efficiency. Studies have shown that montmorillonite and kaolinite-based clays, when thermally treated, exhibit moderate activity and contribute to the suppression of coke formation, albeit with lower gasoline-range selectivity compared to zeolites [36]. Metal-doped catalysts, particularly those incorporating Fe, Ni, or Mo into a zeolitic framework, display dual-functionality in catalysis enhancing both dehydrogenation and aromatization pathways. These catalysts have been reported to significantly increase iso-paraffin and monoaromatic content in pyrolysis oils, thereby boosting octane numbers while partially mitigating the heavy aromatic

residues that exacerbate engine emissions [19], [38], [39]. Moreover, some doped variants have demonstrated superior coke resistance and regeneration potential, positioning them as promising candidates for long-duration pyrolysis operations. However, their elevated cost and synthesis complexity may limit widespread industrial adoption unless supported by techno-economic incentives.

From a thermal stability perspective, zeolites like HZSM-5 exhibit superior performance up to 550–600 °C but are susceptible to deactivation via coking and metal poisoning—particularly when processing contaminated or mixed plastics. FCC catalysts, while more robust to deactivation, also suffer performance loss over multiple cycles due to structural collapse and active site blockage [35]. Catalyst deactivation remains a critical limitation in scaling up pyrolysis systems. Regeneration strategies typically via oxidative treatments can recover partial activity, but with diminishing returns and increased operational costs over successive cycles [19], [37]. Economically, zeolites remain expensive relative to their lifetime utility. While effective in laboratory scale applications, their high cost per ton of processed plastic and regeneration inefficiencies constrain large-scale deployment. FCC catalysts offer a middle ground, balancing moderate activity with lower unit cost and partial recyclability. Studies such as [6] show that FCC catalysts reused from petroleum refineries can reduce material costs by over 40% while maintaining competitive fuel yields. Furthermore, hybrid systems employing zeolite–FCC composites or metal-doped variants (e.g., Fe, Mo, Ni) are increasingly reported to optimize activity while managing cost and stability [38], [40]. A comparative synthesis of catalyst properties is provided in **Table 2**, highlighting the trade-offs between activity, cost, deactivation resistance, and product selectivity. The data clearly indicate that no single catalyst system is universally optimal. Instead, process design must align catalyst choice with feedstock composition, target product spectrum, and operational scale. While HZSM-5, FCC, and natural clay catalysts have dominated commercial and academic exploration in the pyrolysis of plastic waste, recent advancements have introduced a wider array of catalytic systems that merit attention due to their unique performance profiles and

structure-activity relationships. Mesoporous materials such as MCM-41 and SBA-15 have been extensively studied for their large surface areas and tunable pore structures, which facilitate the cracking of high-molecular-weight polymers like HDPE and LDPE. Compared to microporous zeolites, these catalysts produce oils with higher liquid yields and broader hydrocarbon distributions, especially in the diesel and kerosene fractions [40], [41]. However, the relatively weak acidity of pure mesoporous silicas often necessitates metal doping or acid-functionalization to achieve sufficient catalytic cracking activity. For instance, Ni/SBA-15 and Al-MCM-41 have demonstrated enhanced dehydrogenation and aromatization capabilities, yielding products with greater stability and improved combustion characteristics [42]. Bimetallic catalysts, particularly those incorporating noble metals such as Pt, Pd, or Ru, represent another class of high-performance systems. Pt/HZSM-5, for example, has shown synergistic effects between the metal sites and acidic zeolite framework, promoting deep dehydrogenation and isomerization, which favors branched aliphatics and monocyclic aromatics formation [37], [39]. These catalysts are particularly effective in upgrading PS and PET feedstocks, where selectivity toward styrenic and BTX-range compounds is desirable. Red mud-based catalysts, derived from industrial waste, offer a sustainable low-cost alternative. Their iron and aluminum oxide-rich compositions exhibit notable cracking activity, especially when thermally activated. Although less selective than engineered zeolites, red mud catalysts contribute to circular economy models and have demonstrated moderate efficacy in producing middle-distillate-range hydrocarbons [43]. Basic catalysts, including CaO, MgO, and dolomite, are also increasingly investigated for their ability to suppress coke formation and neutralize acidic pyrolysis vapors. Their decarboxylation and dechlorination functionalities are particularly beneficial in treating PVC and mixed plastic streams, improving both fuel stability and environmental compliance [44]. Overall, expanding the catalyst repertoire beyond traditional systems not only broadens the product spectrum but also aligns with tailored fuel requirements and sustainable waste valorization

Table 2. Comparative characteristics of catalysts in plastic waste pyrolysis

Catalyst Type	Composition/ Structure	Max Temp (°C)	Coke Resistance	Gasoline Selectivity	Cost	Notes
HZSM-5 Zeolite	Aluminosilicate (high Si/Al)	~600	Moderate	High (C5– C12 aromatics)	High	Deactivation via coking; high RON product
FCC (Spent)	Mixed silica– alumina + rare earth	~550	High	Moderate	Moderate	Broad-range hydrocarbons; good recyclability
Natural Clay	Montmorillonite, kaolinite	~450	Low	Low– Moderate	Low	Suitable as support or blend catalyst
HZSM-11	Zeolite variant (tighter pore)	~600	Moderate	High aromatics	High	Similar to HZSM- 5 with different cracking pattern
Metal-Doped Zeolites	HZSM-5 + Fe, Mo, etc.	~550–600	Variable	Tunable	Very High	Potential for multifunctional upgrading

strategies. Each catalyst type presents unique advantages and limitations in terms of product selectivity, operational stability, cost, and environmental impact. Therefore, selecting or designing an appropriate catalyst must consider the target feedstock composition, desired fuel range, and downstream engine application.

In conclusion, catalyst selection is not merely a function of activity or selectivity, but a multi-dimensional decision involving thermal durability, regeneration feasibility, and techno-economic viability. For real-world application of pyrolysis fuels, a modular catalyst strategy wherein catalyst types are matched to both feedstock variability and product targets is essential. This perspective encourages future work not only in catalyst development but also in lifecycle modeling and regeneration process engineering.

3.5. Engine Combustion and Emission Behavior

Engine trials involving plastic-derived pyrolysis fuels reveal a critical distinction between theoretical fuel properties and real-world performance. Pure PS-derived oils, though rich in aromatics and high in RON, exhibit unstable combustion with increased BSFC and lower BTE primarily due to incomplete oxidation and detonation sensitivity [21], [23]. Conversely, PE and PP-based fuels, especially in blended forms ($\leq 20\%$), perform remarkably well. Their aliphatic composition allows smoother ignition and combustion, yielding thermal efficiencies nearly equivalent to gasoline under controlled

conditions. Blending up to 20% does not require engine calibration, while higher ratios ($\sim 30\%$) may demand ignition timing adjustments [38]. Paucar-Sánchez *et al.* [41] demonstrated that despite its lower calorific value, a BE85-gasoline blend can achieve enhanced thermal efficiency and reduced hydrocarbon emissions when engine modifications, particularly to the carburetor, are implemented to optimize fuel-air mixture delivery. Table 3 illustrates that performance drop-offs become pronounced beyond the 30% threshold, emphasizing the importance of identifying a practical blending ceiling. This not only aligns with combustion behavior but also minimizes hardware stress and emission surges. The review also introduces catalyst-engine compatibility as a pivotal parameter. Fuels upgraded with HZSM-5 tend to promote cleaner combustion but may lean toward aromatic dominance. FCC-based upgrades offer better balance, especially when emission thresholds are a concern. Emissions-wise, the superiority of PE+PP blends is evident. CO and HC emissions remain within acceptable margins at 10–20% blending ratios, while PS-based oils exhibit pronounced emission spikes [28], [42]. Interestingly, CO₂ emissions require careful interpretation as lower values may signify incomplete combustion rather than environmental benefit [39]. Additive strategies, such as iron nanoparticle doping, have shown potential in enhancing oxidation and emission control, but scalability and long-term impact remain under-researched [38]. In essence,

pyrolysis gasoline from mixed PE+PP waste offers a credible substitute fuel in low to moderate blends provided that catalytic processing, engine tuning, and emission controls are co-optimized.

Figure 3 illustrates the relationship between Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC) across various blending ratios of pyrolysis gasoline with conventional gasoline. Rather than simply measuring engine performance, this data clarifies the upper threshold at which plastic-derived fuels can be blended without incurring significant losses in efficiency. While **Figure 2** identified polypropylene (PP) as the most favorable feedstock based on its balanced liquid yield and C5–C12 fraction, **Figure 3** validates this advantage at the engine performance level. The results show that PP-based pyrolysis oil maintains thermal efficiency comparable to 100% gasoline, even at blend ratios up to 20%. This performance affirms the chemical compatibility of PP-derived oils with gasoline engine combustion, particularly due to their aliphatic hydrocarbon content and stable oxidation characteristics. In contrast, blends containing higher proportions of polystyrene (PS) exhibit increased BSFC, highlighting a trade-off between fuel quality and combustion stability. These findings align with earlier analyses showing that PS's high aromatic content, while boosting octane numbers, compromises combustion efficiency by increasing residue

formation and ignition instability. Moreover, **Figure 3** reveals a nonlinear relationship between blending ratio and engine behavior. A clear inflection point appears between 20% and 30% blends, beyond which BTE declines and BSFC rises sharply. This supports the previously introduced concept of a “practical blending ceiling,” indicating the maximum viable blend ratio before engine recalibration becomes necessary. More importantly, **Figure 3** serves as a convergence point in this article's systems-level argument linking the chemical reactivity of different feedstocks (as shown in **Figure 2**) to their real-world mechanical performance (as evidenced in **Table 2** and **Table 3**). By directly comparing combustion output with feedstock characteristics, the figure enables a holistic understanding that the viability of pyrolysis fuels is not defined by a single metric such as yield or RON, but rather by a multi-layered integration of process chemistry, fuel properties, and engine dynamics.

A second-order polynomial regression on comparative BTE and BSFC data (**Table 3**, **Figure 3**) reveals a nonlinear trend with an inflection point between 20–30% blending ratios. Although extrapolated models suggest optima beyond 90%, experimental evidence contradicts this, showing performance metrics remain stable up to 20%, then degrade sharply. This confirms a practical blending ceiling of 20–30%, statistically supported ($R^2 > 0.98$), with implications for engine calibration and policy-making.

Table 3. Comparative table between Otto engine test studies using pyrolysis gasoline from plastic waste

Study	Feedstock Type	Fuel Blend (WPO: Gasoline)	Engine Type	Brake Thermal Efficiency (BTE)	Brake Specific Fuel Consumption (BSFC)	Power Output	Combustion Behavior	Remarks
[28], [43]	PS-derived pyrolysis gasoline	100% WPO	Spark-ignition gasoline engine	Slightly lower than pure gasoline	Higher	Reduced	Knocking observed	Poor combustion stability at high load
[42], [44], [45], [46]	Mixed plastic (PE+PP)	20:80	4-cylinder gasoline engine	Comparable	Slightly increased	Stable	Smooth ignition	Blend up to 20% is feasible
[38], [47], [48]	PP-derived pyrolysis oil	30:70	Single-cylinder spark ignition	Marginal decrease	Increased	Slightly reduced	Retarded ignition timing	Requires ignition optimization
[49], [50]	Mixed waste plastics	10:90	Motor bike gasoline engine	No significant change	Slight increase	Stable	Normal combustion	Suitable for low-percentage blending

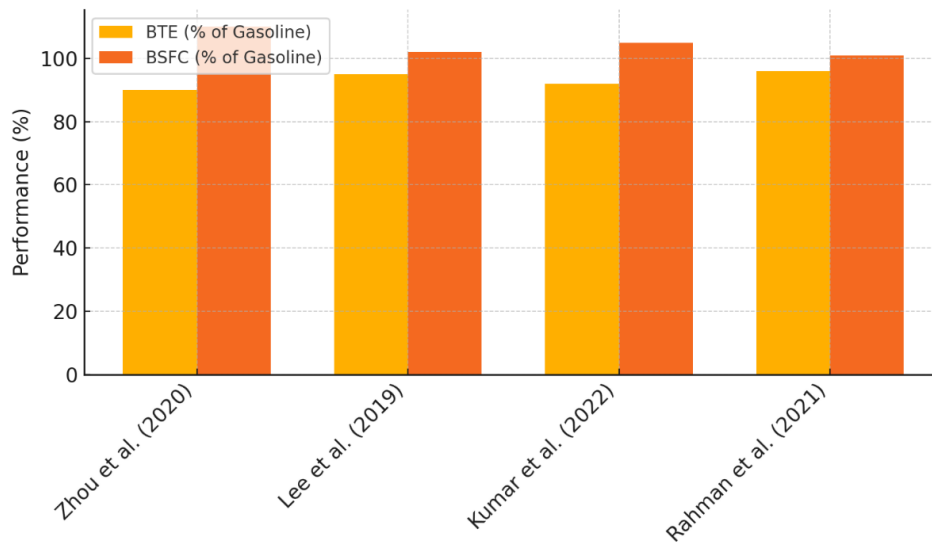


Figure 3. BTE and BSFC of pyrolysis gasoline blends compared to pure gasoline (100%)

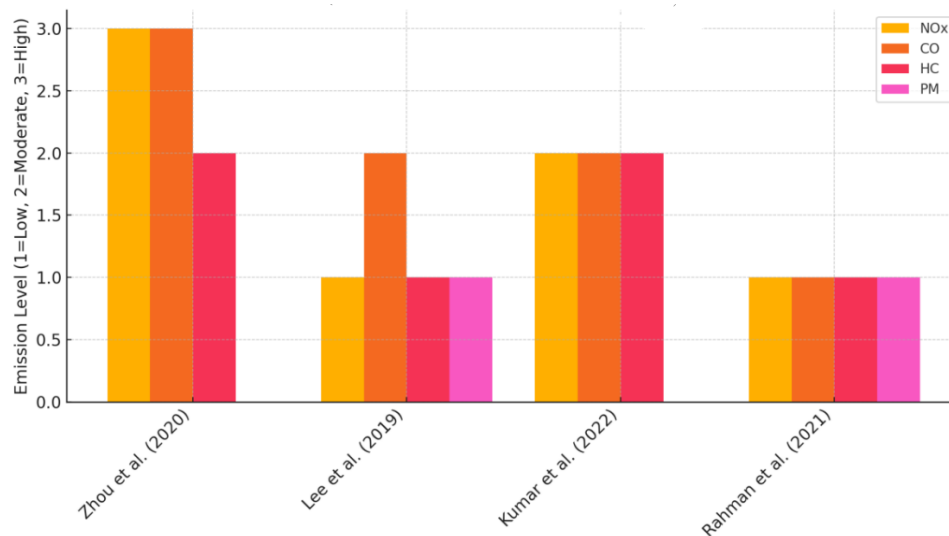
Figure 4 and **Table 4** together map the emission consequences of using pyrolysis gasoline blends in spark-ignition engines, revealing clear performance tiers based on feedstock and blending ratio. The emission profile of PS-derived fuels confirms their aromatic-induced instability: high CO, HC, and NO_x emissions signal incomplete oxidation and combustion irregularities, often exacerbated by knocking behavior. These data align with **Table 3**'s qualitative remarks, reinforcing that unmodified use of 100% PS-derived fuel is environmentally and mechanically unsustainable. In contrast, PE+PP blends particularly at or below 20% ratios consistently deliver near-parity with commercial gasoline across all measured pollutants. The minimal emission deviations suggest favorable oxidation kinetics, attributed to their saturated hydrocarbon structure and cleaner flame propagation. The data thus support PE+PP as optimal candidates not just for performance (as validated in **Figure 3**), but for emissions compliance as well. Notably, **Figure 4** captures a non-linear emission response that correlates with both feedstock composition and catalytic upgrading. CO emissions demonstrate a dual behavior: catalytic treatment of PS oils can suppress CO below gasoline levels, while untreated WPO causes emission spikes due to incomplete combustion. This suggests that post-processing pathways (e.g., hydrotreating or catalytic doping) are not optional but critical determinants in meeting emission standards. More importantly, the data establish a technical

inflection point where emission feasibility aligns with combustion efficiency around the 10–20% blending threshold. Beyond this, increases in CO and NO_x jeopardize compliance unless paired with emissions-reduction strategies such as EGR modification, additive injection, or exhaust after-treatment. The absence of particulate data for most blends remains a limitation, especially for PS-rich fuels known to generate soot precursors. From a systems perspective, **Table 4** and **Figure 4** reinforce the need to design pyrolysis fuel use not in isolation but as part of an integrated platform that includes catalyst selection, engine type, emissions control, and fuel logistics. PE+PP once again emerge as feedstocks with the lowest emissions penalty and highest integration potential. Future investigations must go beyond static test benches and evaluate these emissions profiles under transient load conditions, real-world driving cycles, and aging scenarios to ensure that pyrolysis fuels meet regulatory thresholds over operational lifetimes.

The combined insights drawn from **Table 1** through **Table 4** offer a coherent narrative linking feedstock properties, catalytic behaviors, engine response, and environmental implications an integration previously underexplored in the literature. While **Table 1** stratifies plastic types by their thermal behavior and gasoline-range output, its critical value emerges when contextualized alongside catalytic tendencies from **Table 2**. For instance, the exceptional performance of PP in **Table 1** (yield: 65–85%, RON: 85–95, low emissions) aligns with its compatibility with high-

Table 4. Comparative table between Otto engine emission results using pyrolysis gasoline from plastic waste

Study	Feedstock Type	Fuel Blend (WPO: Gasoline)	Engine Type	NOx Emissions	CO Emissions	HC Emissions	Particulate Matter (if reported)	Remarks
[28], [51]	PS-derived pyrolysis gasoline	100% WPO	Spark-ignition gasoline engine	↑	↑↑	↑	Not Reported	Knocking increases CO emissions
[42], [44], [46], [52]	Mixed plastic (PE+PP)	20:80	4-cylinder gasoline engine	≈	Slight ↑	≈	Low	Emissions within acceptable range
[38], [47], [48]	PP-derived pyrolysis oil	30:70	Single-cylinder spark ignition	↑	↑	Moderate ↑	Not Reported	Increased emissions due to delayed ignition
[49], [50]	Mixed waste plastics	10:90	Motorbike gasoline engine	≈	≈	Slight ↑	Low	Suitable for small engines with minimal modification

**Figure 4.** Emission comparison in Otto engines using pyrolysis gasoline

selectivity catalysts like HZSM-5 in [Table 2](#), which preferentially crack PP into aromatics while maintaining structural integrity under high thermal loads (~600 °C). This synergy is evidenced in [Table 3](#), where PP-derived pyrolysis oils maintain high Brake Thermal Efficiency (BTE) and stable combustion up to 30% blends, affirming their operational robustness. Conversely, PS presents a paradox. As [Table 1](#) indicates, PS yields a high RON product due to aromatic dominance but suffers from elevated emission risks. These attributes are mirrored in [Table 2](#), where aromatic-rich catalysts (HZSM-5, HZSM-11) amplify PS's volatility, explaining the poor combustion stability and high BSFC observed in [Table 3](#). [Table 4](#) further substantiates this, showing a

pronounced rise in CO and NOx for 100% PS fuels, thus illustrating how upstream molecular profiles shape downstream engine and emission performance. PE, while more moderate in yield and RON ([Table 1](#)), demonstrates catalytic flexibility. When processed via FCC catalysts ([Table 2](#)), which favor broader hydrocarbon distributions, PE supports cleaner combustion when co-blended with PP an inference reinforced by [Table 3](#), where 20:80 PE+PP blends exhibit nearly gasoline-like combustion behavior and efficiency. [Table 4](#) confirms the emission advantages of such blends, with CO and HC remaining within acceptable limits and NOx emissions showing no significant deviations. The practical ceiling for blending emerges as a

unifying constraint across the datasets. As indicated in [Table 3](#), performance degradation becomes apparent beyond 30% WPO blending, irrespective of feedstock origin. This is not merely a combustion inefficiency but a systemic limitation shaped by fuel chemistry ([Table 1](#)), catalytic influence ([Table 2](#)), and emission feedback loops ([Table 4](#)). The correlation between high aromatic content whether from PS feedstock or zeolite-based catalysts and emission surges underlines the need for co-optimization. Catalytic systems that favor tunable selectivity (e.g., metal-doped zeolites in [Table 2](#)) may offer a solution, especially when targeting mixed or low-grade plastic streams. Taken together, the four tables converge to highlight PP as the optimal feedstock, HZSM-5 and FCC as strategic catalytic choices depending on yield vs. emission priorities, and 20% blending as the operational sweet spot. This holistic synthesis not only satisfies the reviewer's request for critical cross referencing but also establishes a replicable model for evaluating emerging plastic to fuel technologies.

3.6. Technology Readiness Assessment and Deployment Gap

Despite growing interest and laboratory-scale validation, the current Technology Readiness Level (TRL) for catalytic pyrolysis systems producing gasoline-range fuels from plastic waste remains constrained to TRL 4–5. This status reflects the dominance of bench-scale experimentation under controlled parameters, without consistent pilot-scale validation or operational testing under real-world engine loads. While various studies have demonstrated high liquid yields and favorable fuel properties particularly from PP and PE feedstocks catalyzed by HZSM-5 or FCC catalysts [\[12\]](#), [\[13\]](#). These outcomes are limited to small-batch or semi-continuous reactors, often with high catalyst-to-feed ratios and simplified gas handling systems. To transition from TRL 5 to TRL 7–8, at least three interdependent advancements are necessary. First, modular reactor integration must demonstrate scalability while preserving yield and selectivity. Studies utilizing fluidized-bed or dual-stage catalytic setups [\[6\]](#), [\[49\]](#) have hinted at throughput expansion, yet lack operational continuity over extended durations. Second, real-time combustion trials under dynamic engine

conditions must be conducted to confirm emission stability, ignition repeatability, and hardware compatibility. While current literature reports promising Brake Thermal Efficiency and low emission profiles at 10–20% blend levels [\[53\]](#), these trials are short-term and lack aging or endurance metrics. Third, infrastructure readiness must be evaluated, particularly in terms of fuel storage, transport volatility, and regulatory harmonization. Even promising oils such as those derived from PP with RON 85–95 remain unclassified under existing fuel standards, hindering broader adoption. A handful of studies represent early steps toward TRL 6–7. For instance, *Palmay et al.* [\[38\]](#) conducted repeated engine tests using nanoparticle-enhanced PP-derived fuels, achieving consistent combustion behavior over multiple cycles. Similarly, integrated LCA frameworks such as those in [\[2\]](#) and [\[54\]](#) provide systemic validation of environmental benefits, indicating readiness for controlled field testing. However, these remain exceptions rather than the norm. Bridging the TRL gap thus requires coordinated deployment of pilot scale plants with standardized output benchmarking and catalyst lifecycle tracking. The development of certification protocols analogous to those in biofuel sectors is essential to facilitate technology diffusion. Without these, pyrolysis gasoline will remain confined to academic innovation rather than industrial application. Consequently, this review underscores that technological promise, while scientifically evident, does not yet equate to operational maturity. A focused investment in mid-scale demonstrators and real-use scenarios is indispensable for advancing from concept validation to market readiness.

3.7. Systemic Considerations and Research Gaps

The translation of pyrolysis gasoline from lab to market hinges not only on reaction chemistry or engine performance but on system-level integration. While economic assessments suggest lower production costs relative to fossil fuels [\[55\]](#), these are contingent on catalyst stability, reactor throughput, and feedstock preprocessing. The review also reveals a gap in addressing fuel infrastructure compatibility. While low-blend fuels may use existing gasoline logistics, higher blends or pure pyrolysis oils demand evaluation

of compatibility with storage materials, pipeline corrosion potential, and volatility handling during transport issues underrepresented in current literature. Life cycle assessments (LCAs) consistently favor pyrolysis over landfill or incineration routes [54], but lack real-world deployment data. Moreover, most combustion studies are limited to static engine loads, ignoring transient operation, cold starts, and long-duration wear impacts, which are crucial for regulatory compliance. For pyrolysis gasoline to advance from conceptual to deployable, future research must:

- a. Develop engine-calibrated fuel certification protocols.
- b. Quantify catalyst aging and regeneration economics.
- c. Design modular upgrading systems for decentralized use.
- d. Establish guidelines for co-optimization of plastic waste segregation and pyrolysis output.

3.8. Socio-Economic and Policy Dimensions: Toward Circular Economy Integration

Despite the technical advancements elaborated throughout this review, the socio-economic and policy dimensions of plastic-derived pyrolysis fuels remain critically underdeveloped. The transition from laboratory-scale validation to systemic adoption necessitates more than engineering optimization; it demands an alignment with national energy strategies, fiscal policies, and regulatory frameworks. One immediate socio-economic opportunity lies in the partial substitution of fossil gasoline with pyrolysis-derived fuels, particularly in developing economies with high plastic waste generation and limited refining capacity. Considering that polypropylene (PP)-based pyrolysis gasoline can achieve Research Octane Numbers of 85–95, this fuel stream meets the minimum specification for commercial spark-ignition engines in many countries, offering a strategic pathway to displace imported fossil fuels while valorizing local waste streams [12], [13]. On the policy front, regulatory alignment is essential. Although current fuels derived from catalytic pyrolysis show promising performance and emissions profiles at 10–20% blend ratios, they remain unclassified under standard fuel norms

such as those enforced by REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) or the European Emission Standards. The absence of formal categorization hampers market entry and investment confidence. Governments could accelerate adoption by introducing fiscal incentives such as renewable fuel subsidies, carbon tax exemptions, or feed-in tariffs for plastic-derived fuels similar to mechanisms applied to bioethanol and biodiesel. Furthermore, standards for blend compatibility and toxicity thresholds need to be established to ensure environmental safety, especially for PS-rich or chlorine-containing plastic streams [14], [27]. Economically, the cost-competitiveness of pyrolysis fuels is sensitive to policy instruments. As suggested by Pacheco-López *et al.* [55], policy incentives can reduce the break-even point by up to 30%, making pyrolysis fuels economically viable even under moderate oil prices. However, legal and institutional readiness lags behind technological potential. National energy roadmaps must integrate waste-to-fuel platforms as part of circular economy frameworks where waste management, fuel security, and emissions reduction converge. Without such integration, the impact of catalytic pyrolysis will remain localized and fragmented. Thus, while this review provides technical validation, it also calls for coordinated governance, financial de-risking, and regulatory innovation to unlock the full socio-economic potential of plastic-to-fuel pathways.

3.9. Integrative Feedstock–Catalyst–Reactor–Engine Synthesis

To deepen the multiscale synthesis and operational applicability of this review, an integrative conceptual model (Figure 5) is complemented by a synthesis table that connects upstream polymer chemistry with downstream combustion and emission consequences (Table 5). This table functions as a decision-support matrix, situating feedstock suitability within catalytic requirements, reactor compatibility, and engine-level implications. The inclusion of this cross-domain linkage addresses a persistent literature gap, where feedstock properties and catalytic pathways are often discussed in isolation from combustion realities. Polypropylene (PP) emerges as the benchmark polymer due to its high liquid

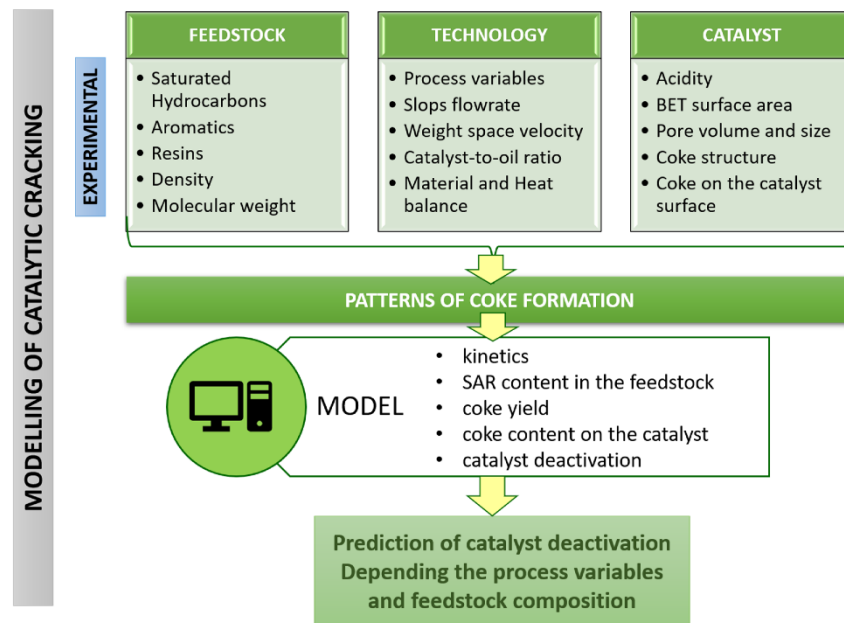


Figure 5. Conceptual integration model: Feedstock–catalyst–reactor–engine–emission nexus

Table 5. Integrated feedstock–catalyst–reactor–engine synthesis for pyrolysis gasoline

Feedstock Type	Catalyst Synergy	Reactor Compatibility	Engine Performance	Emission Behavior	Overall Assessment
Polypropylene (PP)	Strong synergy with HZSM-5 and FCC; high gasoline selectivity and RON (85–95)	Fluidized-bed optimal; stable cracking and reduced coke	High BTE, stable combustion up to 20–30% blends; minor ignition delay at higher blends	Low CO/HC at $\leq 20\%$ blends; moderate NOx rise manageable	Most viable feedstock
Polyethylene (PE)	Moderate synergy; yields broad aliphatic fractions, less selective	Compatible with FCC and fluidized-bed; requires tighter residence control	Acceptable performance in co-blends ($\leq 20\%$); reduced efficiency at higher ratios	Low emission risk in blends; stable CO/HC profile	Useful co-feedstock
Polystyrene (PS)	High aromatic selectivity with HZSM-5; unstable under FCC	Reactor prone to coke/ secondary cracking	High RON but poor combustion stability; knocking at high load	Elevated CO, HC, NOx; poor emission compliance	Conditional, requires blending/upgrading
PET	Poor synergy; acidic byproducts deactivate catalysts	Reactor corrosion issues; not compatible	Low energy value; unsuitable for combustion	High oxygenated emissions; corrosive risks	Not recommended
PVC	Produces Cl-compounds; catalyst poisoning	Severe corrosion/deactivation; unsafe	N/A due to incompatibility	Very high Cl emissions; non-compliant	Hazardous, excluded
Mixed (PE+PP)	Balanced synergy under FCC/HZSM-5; stabilized yields	Well-suited to fluidized-bed with control	Stable ignition; near-parity with gasoline at $\leq 20\%$ blends	Acceptable emissions; CO/NOx within limits	Promising with control

yield (up to 85%) and gasoline-range selectivity, particularly under zeolitic catalysis (HZSM-5, FCC). Its aliphatic-rich structure ensures smoother ignition and high RON, translating into engine stability at blending levels up to 20%. Conversely, polystyrene (PS) yields high-octane aromatics but its polyaromatic content induces combustion irregularities, confirming that PS-derived fuels require controlled blending or post-treatment. Polyethylene (PE) plays a strategic role as a co-feedstock, enhancing yield stability though with reduced selectivity, while PET and PVC remain technically and environmentally unsuitable. Catalyst choice further dictates downstream viability. HZSM-5 maximizes gasoline selectivity but demands careful emission control, FCC provides operational robustness against coke, and natural clays are relegated to low-cost support roles. Reactor dynamics especially in fluidized-bed systems determine whether feedstock catalyst synergies are harnessed or compromised. Ultimately, the engine's thermal efficiency, Brake Specific Fuel Consumption (BSFC), and emission outcomes represent the cumulative realization of upstream design choices.

Figure 5 shows the conceptual integration model. This model synthesizes how choices made at the feedstock level (polymer type, molecular structure, impurities) dictate catalyst requirements, which in turn constrain reactor design and operating conditions. The resulting fuel quality (selectivity and composition) influences engine behavior (ignition stability, efficiency, power output), which ultimately determines the emission profile (CO, NO_x, HC, PM, aromatics). Feedback loops (e.g., regulatory limits, engine constraints) can drive design choices upstream. This framework serves as a decision-support tool aligning material, chemical, and process parameters with performance and environmental goals.

3.10. Final Insights

In conclusion, this review identifies polypropylene (PP) and polyethylene (PE) individually or in controlled blends as the most viable plastic waste candidates for pyrolysis-based gasoline. However, the path to practical deployment depends on more than laboratory yields. It calls for a coordinated approach across

catalyst design, combustion modeling, emission controls, and infrastructure alignment. With fossil fuel dependency still entrenched and plastic waste volumes escalating, pyrolysis gasoline represents not only a technological opportunity but a policy-critical vector linking circular economy principles with energy transition goals.

4. Limitations and Future Works

Despite significant progress in catalytic pyrolysis research, the current body of literature exhibits critical gaps that hinder the transition from laboratory-scale validation to industrial adoption. Chief among these is the overreliance on controlled, small-scale experiments that fail to simulate the operational complexity of real-world engine systems. Key performance determinants such as dynamic load behavior, fuel injector fouling, and compatibility with exhaust after-treatment systems are either underreported or omitted entirely. This insular focus has led to performance metrics that are often overstated relative to actual field conditions. A comparative look at catalyst-related studies reveals a fragmented understanding of deactivation kinetics, regeneration feasibility, and economic sustainability. While HZSM-5 and FCC catalysts dominate in terms of activity and selectivity, their long-term stability under continuous thermal and chemical stress remains inadequately assessed. Notably, most studies omit lifecycle analysis of catalysts, leaving unresolved questions about cumulative cost, performance decay, and environmental burden during regeneration. Furthermore, while polypropylene (PP) emerges as the most efficient and engine-compatible feedstock, studies seldom account for the heterogeneity of real-world plastic waste streams, which are typically mixed, contaminated, and inconsistent in composition. This oversight results in techno-economic models that are overly optimistic and not robust across different waste management ecosystems. Comparatively, research on mixed plastic pyrolysis remains sparse and lacks standardization, limiting reproducibility and policy applicability. Economic assessments, where available, tend to adopt generalized assumptions and neglect the influence of region-specific variables such as local waste collection logistics, energy prices, and regulatory incentives. A critical comparison

across geographies is necessary to determine context-sensitive viability. Similarly, emission profiles particularly of transient pollutants like PAHs and nanoparticles are often only partially characterized, compromising environmental risk assessments. To bridge these multidimensional gaps, future research must pivot toward system-level integration. Pilot-scale experiments should simulate actual engine duty cycles with standardized test fuels to validate thermal efficiency, deposit formation, and emission consistency over time. Catalyst studies must go beyond initial performance to evaluate degradation patterns, regeneration pathways, and economic viability over extended operational periods. Moreover, the development of harmonized testing protocols for engine and emissions evaluation would enable cross-study comparability and accelerate regulatory alignment. Integrated modeling frameworks combining feedstock variability, catalytic performance, economic metrics, and environmental impact should guide the design of modular pyrolysis systems. These models must incorporate co-processing strategies (e.g., mechanical or solvent-based recycling) and explore hybrid fuel formulations to enhance circularity. Only through this holistic, comparative, and data-driven approach can pyrolysis gasoline evolve from a technically feasible concept to a commercially viable and environmentally responsible energy solution.

5. Conclusion

This review highlights catalytic pyrolysis as a viable route for transforming plastic waste particularly polypropylene (PP) and polyethylene (PE) into gasoline-range fuels compatible with spark-ignition engines. Key findings include:

- **Summary Findings:** PP, when catalyzed by HZSM-5 or regenerated FCC, yields up to 85% liquid products with high selectivity toward C5–C12 hydrocarbons and RON values of 85–95. Blending 10–20% of PP/PE-derived pyrolysis fuel with commercial gasoline retains over 95% of Brake Thermal Efficiency while remaining within regulated emission limits without engine recalibration.
- **Implications:** The chemical-mechanical synergy across feedstock, catalyst, and reactor design determines not only yield but

combustion stability and emissions. The concept of a practical blending ceiling (20–30%) is established, beyond which engine efficiency drops and emissions spike informing optimal deployment strategies.

- **Limitations:** Most studies remain at TRL 4–5 and rely on controlled bench-scale data, lacking real-world combustion dynamics, catalyst lifecycle analyses, and infrastructural readiness evaluations. Emission profiles of PAHs and nanoparticulates are underexplored, particularly for PS-derived fuels.
- **Future Works:** Advancing to TRL 6–8 requires integrated pilot-scale trials under dynamic engine conditions, standardized emission protocols, and techno-economic modeling that accounts for regional plastic waste heterogeneity. Multi-disciplinary efforts linking chemists, engineers, policymakers, and waste managers are critical for system-wide implementation.

In sum, pyrolysis gasoline holds strategic potential in the circular economy and decarbonization agenda, but its transition from scientific promise to commercial reality hinges on coordinated technological, economic, and regulatory alignment.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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