Review Article

Thermochemical and Catalytic Valorisation of Waste Tire Rubber for Gas Production: A Comparative Review of Pyrolysis, Catalytic Upgrading, Solar-Photocatalytic, and Plasma Gasification Routes

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Abstract | The management of end-of-life tyres remains a pressing environmental and economic challenge, and recent years have witnessed considerable progress in thermochemical and catalytic technologies for converting waste tyre rubber into valuable gaseous products. This review provides a comparative, critical analysis of the principal conversion routes reported in the literature conventional thermal pyrolysis, catalytic pyrolysis, solar-photocatalytic pyrolysis, catalytic steam reforming of pyrolysis volatiles, and plasma or conventional gasification with particular attention to how operating conditions, catalyst selection, and tire composition govern the yield and composition of the resulting gas stream (H_2, CO, CO_2, CH_4, and light C_1–C_5 hydrocarbons). The evidence assembled here indicates that catalytic and integrated process configurations, including hot-char-catalysed pyrolysis, Ni/ZSM-5- and Fe_2O_3-catalyzed pyrolysis, and tire-char-catalysed steam reforming, achieve substantially higher hydrogen-rich gas yields and reduced tar and polycyclic aromatic hydrocarbon (PAH) formation relative to uncatalysed thermal pyrolysis, while solar-photocatalytic and plasma-based routes demonstrate the feasibility of coupling renewable energy input or high-temperature ionised media with tire rubber conversion to reach gas yields of up to 41% and 44.6%, respectively. At the same time, each pathway carries distinct technical and economic constraints catalyst cost, energy intensity, reactor complexity, and feedstock logistics that currently limit deployment at industrial scale. The review closes by identifying priority research directions, including techno-economic assessment, catalyst durability under continuous operation, and the integration of tire-derived carbon with co-pyrolysis or chemical-looping schemes, to advance the conversion of waste tyre rubber into clean fuel gases and synthesis gas within a circular-economy framework for end-of-life tyres.

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Introduction

End-of-life tyres accumulate as one of the most persistent forms of black pollution worldwide, a consequence of the chemical resistance of vulcanised rubber to natural degradation and of global tyre production that now exceeds two billion units annually (Han *et al.*, 2023; Afash *et al.*, 2023; Zerin *et al.*, 2023).

Landfilling and open burning the two disposal routes historically relied upon are increasingly constrained by environmental regulation and are, in any case, unsustainable both ecologically and economically. Thermochemical conversion, principally pyrolysis and gasification, has consequently emerged as the most promising route for recovering energy and material value from tyre waste, yielding pyrolysis oil, tire-derived char, and a combustible or synthesis-grade gas fraction (Han *et al.*, 2023; Rogachuk and Okolie, 2024; Zerin *et al.*, 2023).

The distribution of pyrolysis products is strongly governed by tyre formulation specifically the ratio of natural to synthetic rubber and by vehicle class. Tires from light passenger vehicles, richer in natural rubber, decompose over a comparatively narrow thermal window, whereas heavier truck and off-road tyres, formulated with a higher proportion of styrene–butadiene rubber (SBR), display a broader decomposition range and markedly different oil-to-gas ratios (Singh *et al.*, 2018; Čepić *et al.*, 2021). Raising the pyrolysis temperature above roughly 500–550 °C consistently increases gas yield at the expense of the liquid fraction, a consequence of secondary cracking of the primary volatiles (Singh *et al.*, 2018; Nisar *et al.*, 2018; Čepić *et al.*, 2021; Zerin *et al.*, 2023). The gas fraction itself is dominated by hydrogen, carbon monoxide, carbon dioxide, methane, and light C_1–C_5 hydrocarbons (Singh *et al.*, 2018; Nisar *et al.*, 2018).

Research attention has, over the past several years, shifted from simple product characterisation toward deliberately steering the process to favour high-value gases, in particular hydrogen and syngas. Catalytic pyrolysis studies employing Ni/ZSM-5 and Fe_2O_3 report marked improvements in H_2 and CH_4 selectivity through modification of the free-radical pathways responsible for gas formation (Li *et al.*, 2022; Yu *et al.*, 2022), while catalytic steam reforming of pyrolysis volatiles over a tire-char catalyst rather than a costly metal catalyst has achieved hydrogen yields of roughly 223 mmol g^{-1}, corresponding to about 74% of the theoretical maximum (Li and Williams, 2024). Solar-photocatalytic pyrolysis using TiO_2-based catalysts under concentrated sunlight has likewise raised gas yield to 40–41 wt%, compared with roughly 20 wt% for uncatalysed solar pyrolysis (Hijazi *et al.*, 2018).

In parallel, numerical modelling and kinetic analysis thermogravimetric analysis (TGA) and pyrolysis–gas chromatography/mass spectrometry (Py-GC/MS) in particular have clarified the decomposition mechanisms and gas-formation pathways involved. These studies consistently show that increasing temperature raises the hydrogen fraction while reducing the share of C_1–C_4 hydrocarbons in the pyrolysis gas, with reported activation energies typically falling in the range of 100–190 kJ/mol depending on operating conditions and catalyst (Garder and Bogomolov, 2025; Menares *et al.*, 2020; Osorio-Vargas *et al.*, 2021). Recent comprehensive reviews confirm that product distribution oil, char, and gas is governed principally by temperature, reactor configuration, residence time, and catalyst type, with gas yield from thermal pyrolysis of tyres typically falling within a 5–20 wt% range (Han *et al.*, 2023; Zerin *et al.*, 2023; Hamzah *et al.*, 2023, 2023a).

This review examines and compares the principal thermochemical and catalytic routes currently reported for converting waste tyre rubber into gaseous products, with emphasis on operating conditions, resulting gas composition, and the influence of catalyst type and process configuration on gas quality and yield. It further weighs the relative technical, economic, and environmental merits of each pathway and identifies the routes most likely to deliver high-value fuel gas or synthesis gas, supporting more advanced and sustainable management of end-of-life tyre waste.

Effect of operating conditions and tire composition on gas yield and composition

Operating temperature, residence time, and tyre type constitute the principal variables governing the quantity and composition of gas evolved during pyrolysis and gasification of tyre rubber. Elevated temperatures intensify secondary cracking of the primary devolatilisation products, raising the yield of light hydrocarbons (C_1–C_5) and hydrogen, while feedstocks rich in SBR rubber are disproportionately associated with higher hydrogen output. Deliberate manipulation of these two variables temperature and tyre type therefore provides a practical means of steering the process toward either a fuel-gas or a synthesis-gas product slate, according to the intended industrial application. These findings, established primarily through fixed-bed and batch-reactor studies (Singh *et al.*, 2018; Nisar *et al.*, 2018; Čepić *et al.*, 2021), underpin the process-design choices examined

in the sections that follow (Hamzah, 2025).

Role of catalysts and process integration in enhancing gas production

Catalysts markedly alter both the quantity and the selectivity of gas evolved from tyre pyrolysis. Ni/ZSM-5 and iron oxide (Fe_2O_3) have both demonstrated a pronounced capacity to raise gas yield while steering product selectivity toward hydrogen and methane, and pyrolysis char generated in situ performs a comparable function at substantially lower cost (Sridevi *et al.*, 2024, 2026; Varma *et al.*, 2024). Photocatalysts operating under solar irradiation have likewise produced sizeable increases in gas output while reducing reliance on fossil energy input for process heat. Process integration offers a complementary route to gas-quality improvement: Coupling pyrolysis with steam reforming of the resulting volatiles particularly when the reforming step is catalysed by tire-derived char rather than an externally supplied catalyst extends the potential for producing H_2- and CO-rich synthesis gas, although the approach carries appreciable energy and steam demand that must be weighed against the value of the hydrogen recovered (Wang *et al.*, 2020; Li *et al.*, 2022; Yu *et al.*, 2022; Hijazi *et al.*, 2018; Li and Williams, 2024).

Comparative analysis of thermochemical and catalytic conversion technologies

Conventional thermal pyrolysis in batch or fixed-bed reactors remains the principal technological basis for gas recovery from end-of-life tyres. The process is typically operated between 400 and 750 °C under an inert atmosphere, using shredded tyre crumb or granulate as feedstock. Gas yield rises with temperature, particularly above 500 °C, as a consequence of secondary cracking, and the resulting gas stream consists predominantly of H_2, CO, CO_2, CH_4, and light C_1–C_5 hydrocarbons (Singh *et al.*, 2018; Nisar *et al.*, 2018; Čepić *et al.*, 2021). The technology's principal attraction lies in its simplicity and industrial maturity; its principal limitation is a comparatively modest gas yield of 5–20 wt%, with substantial quantities of oil and char generated concurrently (Čepić *et al.*, 2021; Zerin *et al.*, 2023; Hamzah *et al.*, 2026; Hamzah *et al.*, 2026a). Table 1 and Figure 1 summarise these figures alongside the remaining routes discussed below.

Studies examining the influence of tyre type on gaseous products indicate that the combination of tyre formulation and operating temperature can be used deliberately to tune gas composition: Tyres with a higher SBR content generate proportionally more hydrogen at elevated temperature (Singh *et al.*, 2018). Detailed fraction-separation experiments coupled with gas-chromatographic analysis confirm that increasing temperature raises the light-hydrocarbon (C_1–C_5) share of the product gas at the expense of the liquid fraction, providing the quantitative basis needed to design units targeting a specific gas composition (Nisar *et al.*, 2018; Husam *et al.*, 2024).

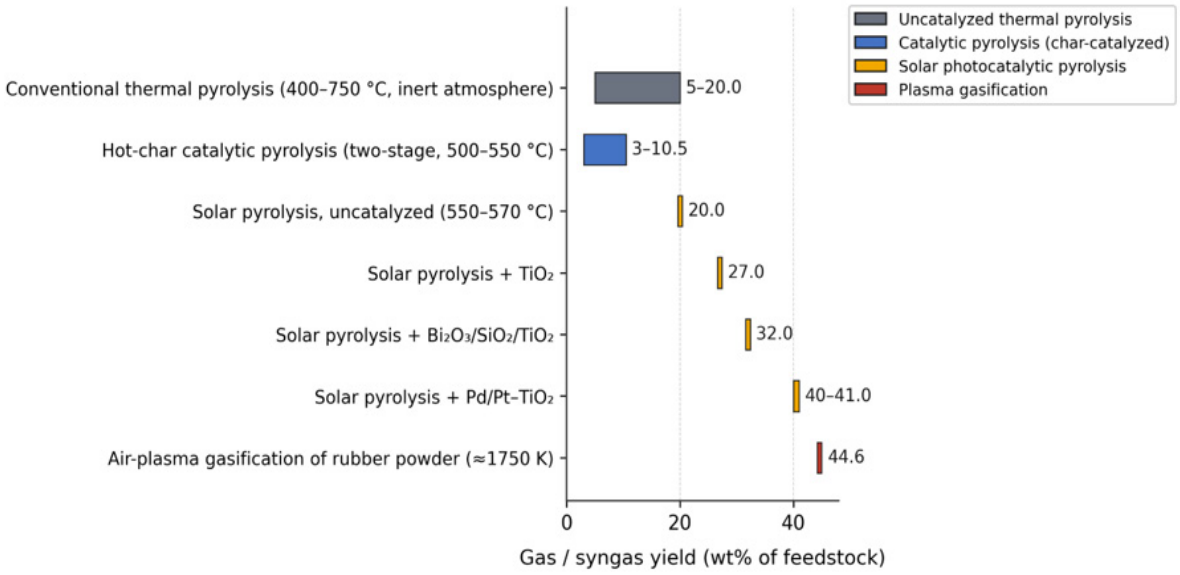

Figure 1: *Comparative gas/syngas yield of thermochemical and catalytic conversion routes for waste tyre rubber (data extracted from Čepić et al., 2021; Zerin et al., 2023; Wang et al., 2020; Hijazi et al., 2018; Messerle and Ustimenko, 2024).*

Table 1: *Comparative summary of thermochemical and catalytic routes for gas production from waste tyre rubber.*

Technology/ Study	Key operating conditions	Gas yield and composition	Advantages and limitations	Primary application	References
Conventional thermal pyrolysis (batch/fixed-bed)	400–750 °C, inert N_2, tire crumb/granulate feed	5–20 wt% gas, rising above 500 °C; H_2, CO, CO_2, CH_4, C_1–C_5	Simple, industrially mature; substantial co-production of oil and char	General fuel gas / process heat	Singh *et al.*, 2018; Nisar *et al.*, 2018; Čepić *et al.*, 2021; Zerin *et al.*, 2023
Tire-type-controlled pyrolysis	650–750 °C; light/ medium/heavy tyre classes, batch reactor	Same gas species; SBR-rich tyres favour higher H_2 at elevated T	Enables gas-composition tuning via feedstock/ temperature selection	Design basis for targeted gas composition	Singh *et al.* 2018
Fraction-resolved pyrolysis with GC analysis	Stepped temperature program; separated gas/ liquid/tar/char fractions	Gas enriched in C_1–C_5 with rising T, at oil's expense	Provides quantitative design data for composition-specific gas units	Light fuel-gas (C_1–C_5) production	Nisar *et al.* 2018
Hot-char-catalysed pyrolysis (two-stage)	Two sequential stages, 500–550 °C; hot tyre char as in-situ catalyst	Gas yield raised from 3 to 10.5 wt%	Low-cost in situ catalyst; reduces PAHs and carbon deposition; needs a suitable char supply.	Improved gas/ oil quality at low catalyst cost	Wang *et al.* 2020
Ni/ZSM-5-catalyzed pyrolysis for H_2	Catalytic pyrolysis with Ni, ZSM-5, Ni/ ZSM-5; MD-simulation-supported	Major gases H_2, CH_4, C_2H_4; Ni/ZSM-5 gives highest H_2 content	High H_2 selectivity, lower required temperature; costly metal catalyst	Dedicated hydrogen-rich gas production	Li *et al.* 2022
Fe_2O_3-catalyzed pyrolysis with mechanistic analysis	Fixed-bed + MD/DFT simulation; commercial Fe_2O_3	Main gases CH_4, H_2, C_2H_4; Fe_2O_3 raises CH_4/H_2, lowers C_2H_4	Enables gas-ratio tuning via catalyst choice and radical-pathway control	Tailored CH_4/ H_2-rich fuel gas	Yu *et al.* 2022
Solar-photocatalytic pyrolysis	550–570 °C, 950–1050 W/m^2 solar flux; TiO_2, Pd/Pt–TiO_2, Bi_2O_3/ SiO_2/TiO_2	Gas 20 wt% uncatalyzed; 27% with TiO_2; 32% with Bi_2O_3/SiO_2/ TiO_2; 40–41% with Pd/ Pt–TiO_2	Harnesses solar energy, strong yield gains; complex, weather- and catalyst-sensitive	Fuel-gas production with reduced fossil energy input	Hijazi *et al.* 2018
Ni/SiO_2-catalyzed pyrolysis (liquid-focused)	350–450 °C; analytical reactor + TGA-FTIR + Py-GC/MS	Catalyst redirects pathways toward aromatics; lowers activation energy, accelerates volatile release	Improves vapor/gas formation at reduced severity; primary focus is oil quality	Product-distribution optimisation at reduced severity	Osorio-Vargas *et al.* 2021
Co-pyrolysis with waste plastics (HDPE, LDPE, PP, PS, PET)	Fixed batch-bed reactor; mixed tire/plastic feed ratios	Main gases H_2, CH_4, C_2H_6, C_2H_4, C_3H_8, C_3H_6, C_4; synergistic yield above additive expectation	Raises and tunes gas yield via plastic co-feed; added feedstock-logistics complexity	Fuel-gas production with tailored oil aromaticity	Alzahrani *et al.* 2024
Gasification + steam reforming with tire-char catalyst	Two-stage: pyrolysis, then steam reforming of volatiles over tyre char, 700–1000 °C	H_2-/CO-rich syngas; H_2 yield ≈ 223 mmol g^{-1} (≈74% of theoretical maximum) at 2 h	Combines char gasification with vapour reforming; high H_2/CO yield; high steam/energy demand.	Hydrogen and syngas for chemical/fuel use	Li and Williams 2024
Air-plasma gasification of rubber powder	Air-plasma, ≈1750 K, rubber-powder feed	44.6% syngas (19.1 vol% H_2, 25.5 vol% CO); 95.6% carbon conversion	High-purity, high-yield syngas; no notable harmful impurities; high energy consumption	H_2/CO syngas for fuel or chemical feedstock	Messerle and Ustimenko 2024
Conventional gasification (review)	Steam, air, or CO_2 gasifying agent; ≈900–1060 K	Gas rich in H_2, CO, CH_4, C_2H_4, C_3H_6; composition set by agent and equivalence ratio	Flexible gas composition; more difficult process control and emissions management	Syngas/fuel-gas recovery at scale	Han *et al.* 2024
Kinetic/numerical modelling of pyrolysis	Finite-element simulation, fixed dense bed, rubber chips (3 mm), 350–650 °C.	Rising T increases H_2, decreases C_1–C_4 share; activation energy ≈188.6 kJ/mol	Design and optimisation tool; reduces experimental burden	Reactor design and operating-condition optimisation	Garder and Bogomolov 2025

Catalytic intervention whether through hot tyre char or metal-oxide catalysts such as Fe_2O_3 has consistently improved both gas quality and gas yield while suppressing PAH formation and carbon deposition; Ni/ZSM-5 in particular produces a hydrogen-rich gas stream, albeit at the cost of an expensive metal catalyst (Wang *et al.*, 2020; Li *et al.*, 2022; Yu *et al.*, 2022). Solar-photocatalytic pyrolysis using TiO_2 and its derivatives has separately demonstrated a substantial increase in gas yield while harnessing solar energy input, although the approach introduces additional system complexity and sensitivity to catalyst formulation and weather conditions (Hijazi *et al.*, 2018), as illustrated in Figure 1.

Co-pyrolysis of tyre rubber with various plastic wastes (HDPE, LDPE, PP, PS, PET) exhibits a synergistic effect that raises gas productivity and modifies gas composition according to the plastic co-feed, at the cost of greater complexity in feedstock logistics (Alzahrani *et al.*, 2024). Combining pyrolysis with steam reforming of the char has separately achieved high yields of hydrogen and synthesis gas, supporting the use of these gases in chemical or industrial-fuel applications, notwithstanding the elevated energy and steam demand this coupling entails (Li and Williams, 2024).

Numerical modelling provides an effective tool for optimising reactor design and operating conditions and for predicting product gas composition without recourse to costly repeated experimentation (Garder and Bogomolov, 2025; Akpan *et al.*, 2026). Comprehensive recent reviews confirm that reactor type, temperature, catalyst, and residence time are the decisive factors governing both gas yield and gas composition, pointing toward the process refinements needed to extract maximum value from tyre recycling (Han *et al.*, 2023; Gao *et al.*, 2022; Zerin *et al.*, 2023).

Beyond pyrolysis, gasification-based routes offer a further means of producing hydrogen- and CO-rich synthesis gas directly. Plasma gasification of tire-rubber powder, operated at a mass-average temperature of approximately 1750 K under an air plasma, converts the great majority of feedstock carbon (95.6%) into a syngas stream containing 19.1 vol% H_2 and 25.5 vol% CO — a 44.6% syngas yield essentially free of harmful impurities though at considerable energy cost (Messerle and Ustimenko, 2024). Conventional gasification using steam, air, or CO_2 as the gasifying agent, typically operated between roughly 900 and 1060 K, offers greater flexibility in tailoring gas composition (H_2, CO, CH_4, C_2H_4, C_3H_6) through the choice of gasifying agent and equivalence ratio, but presents greater challenges in process control and emissions management (Han *et al.*, 2024). Figure 2 situates these gasification routes within the broader set of conversion pathways surveyed in this review, and Table 2 collects the corresponding quantitative performance benchmarks.

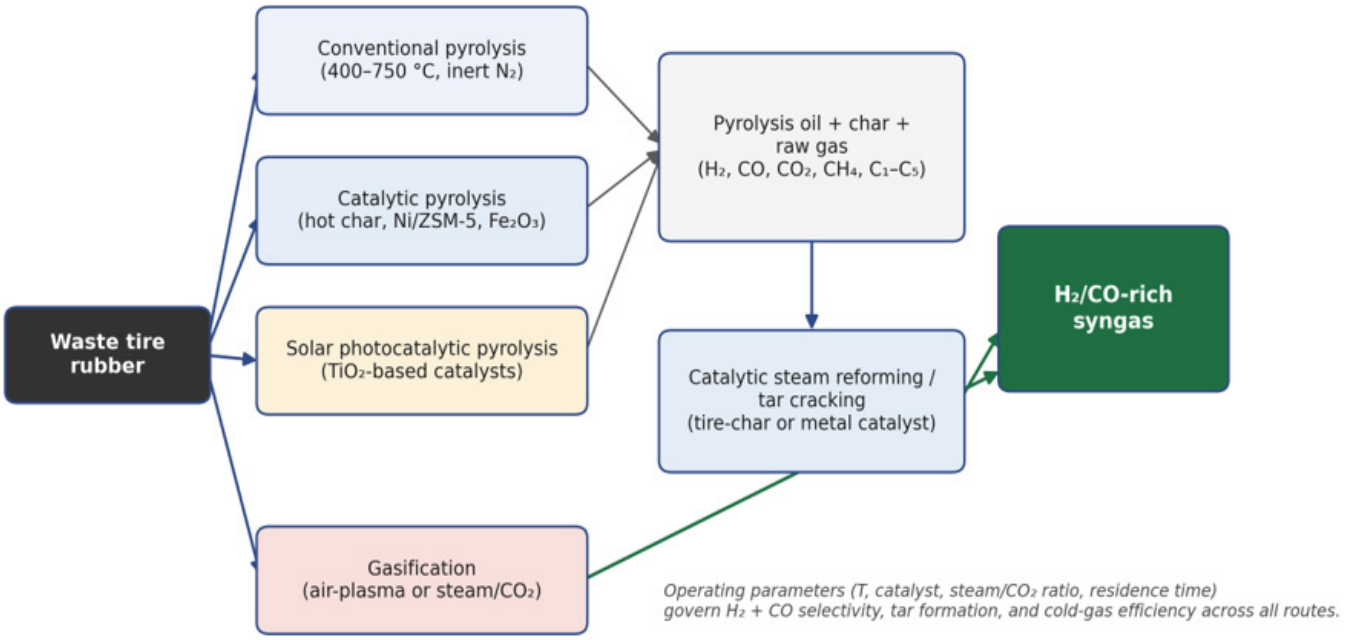

Figure 2: *Overview of thermochemical and catalytic conversion routes for gas production from waste tyre rubber, from feedstock through to H_2/CO-rich synthesis gas.*

Table 2: *Quantitative performance benchmarks for the principal conversion routes.*

Technology	Operating temperature	Gas / Syngas yield	Reference
Conventional thermal pyrolysis	400–750 °C	5–20 wt%	Čepić *et al.* 2021; Zerin *et al.* 2023
Hot-char-catalysed pyrolysis	500–550 °C	3–10.5 wt%	Wang *et al.* 2020
Solar pyrolysis, uncatalysed	550–570 °C	20 wt%	Hijazi *et al.* 2018
Solar pyrolysis + TiO_2	550–570 °C	27 wt%	Hijazi *et al.* 2018
Solar pyrolysis + $Bi_2O_3/SiO_2/TiO_2$	550–570 °C	32 wt%	Hijazi *et al.* 2018
Solar pyrolysis + Pd/Pt–TiO_2	550–570 °C	40–41 wt%	Hijazi *et al.* 2018
Tire-char-catalysed steam reforming	700–1000 °C	H_2: ≈223 mmol g^{-1} (≈74% of theoretical max.)	Li and Williams 2024
Air-plasma gasification	≈1750 K (≈1477 °C)	44.6 wt% syngas	Messerle and Ustimenko 2024

Prospects and challenges for industrial-scale deployment

Despite substantial progress in understanding and optimising these conversion routes, their translation to industrial scale remains constrained by energy efficiency, the complexity of the required process systems, and the cost of high-performance catalysts. Numerical modelling offers a promising means of reducing dependence on costly experimental campaigns while improving reactor design and operating strategy. Looking forward, integrating plastic co-feeds with tyre rubber, together with developing low-cost, environmentally benign catalysts, represents a particularly promising research direction for improving the economic and environmental viability of these technologies. Equally important are systematic techno-economic assessments, extended catalyst-durability trials under continuous operation, and closer integration of tire-derived char with co-pyrolysis or chemical-looping gasification schemes priorities that would substantially strengthen the evidence base needed for industrial deployment.

Conclusion

This review demonstrates considerable diversity among available technologies for producing gas from waste tyre rubber, each carrying distinct advantages and limitations in terms of gas yield, by-product quality, energy demand, and operating cost. Catalytic and integrated process configurations including catalytic pyrolysis, char-based gasification, and photocatalyst-assisted routes consistently achieve higher hydrogen and synthesis-gas productivity with reduced pollutant formation relative to uncatalysed thermal pyrolysis, though the complexity of these systems and the cost of catalysts remain obstacles to industrial-scale expansion. The evidence assembled here underscores the importance of continued development in numerical modelling and process integration to achieve cleaner gas production with improved economic and environmental efficiency, opening promising prospects for managing tire rubber waste and converting it into value-added resources.

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Novelty Statement

Unlike previous reviews that examine tyre pyrolysis or gasification in isolation, this work provides an integrated, quantitative comparison of five conversion routes conventional thermal pyrolysis, catalytic pyrolysis, solar-photocatalytic pyrolysis, catalytic steam reforming, and plasma/conventional gasification under a single evidence framework (Tables 1–2, Figures 1–2). It further links operating parameters, catalyst chemistry, and tyre composition directly to gas yield and hydrogen selectivity, and identifies techno-economic assessment, catalyst durability, and co-pyrolysis/chemical-looping integration as the priority gaps limiting industrial deployment.

Author's Contribution

Almuntadher Alwhelat: Conceptualisation, literature investigation, formal analysis, writing original draft, writing review and editing, corresponding author.

Supervision, validation, writing review and editing.

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Conflict of interest
The authors has declared no conflict of interest.

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