Plastic-Derived Syngas for Metallurgical Applications: Why It Is Not Industrially Viable Yet

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ABSTRACT   **Original Research Article**

Plastic waste has been widely proposed as an alternative carbon source for syngas (CO–H_2) production to support decarbonization strategies in metallurgical operations. In principle, plastic-derived syngas could partially replace fossil-based reductants or fuels in processes such as direct reduction, smelting, roasting, and secondary metallurgy. Despite extensive laboratory- and pilot-scale research, no large-scale metallurgical implementation has been demonstrated to date. This critical review examines the fundamental, operational, and economic barriers that currently prevent plastic-derived syngas from achieving industrial viability in metallurgical applications. Particular attention is given to feedstock heterogeneity, halogen- and heteroatom-derived contaminants (Cl, F, S, N), tar formation, unstable syngas composition, low effective carbon utilization, and incompatibility with metallurgical process requirements. Furthermore, the review highlights critical challenges related to gas cleaning, refractory corrosion, secondary emissions (including HCl, HF, dioxins, and furans), and higher CAPEX and OPEX costs compared with conventional fossil-based syngas routes. By systematically contrasting academic claims with industrial constraints, this review clarifies why plastic-derived syngas remains technologically immature for metallurgy and identifies the research gaps that must be addressed before industrial adoption can be realistically considered.

Keywords: Plastic waste, Syngas, Metallurgical processes, Gasification, Pyrolysis, Chlorine contamination, Tar formation, Industrial viability, Decarbonization.

Highlights

- Plastic-derived syngas remains incompatible with the requirements of industrial metallurgical processes.
- Feedstock heterogeneity leads to an unstable syngas composition and process control issues.
- Halogen- and sulfur-bearing plastics pose severe gas-cleaning and corrosion challenges.
- Tar formation and low carbon efficiency limit large-scale operational reliability.
- High CAPEX and OPEX outweigh environmental benefits given current technological conditions.

Graphical Abstract

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Introduction

Converting plastic waste into syngas has been promoted as a way to reduce plastic leakage and provide alternative carbon and energy to industry. Most work focuses on pyrolysis and gasification because these processes can handle mixed waste streams and yield CO–H$_2$ mixtures (Al-asadi et al., 2020; Bashir et al., 2025; Busto et al., 2025; Shah et al., 2023). Techno-economic and life-cycle studies often report benefits under specific boundary conditions and assume stable long-term operation (Adefeso et al., 2023; Afzal et al., 2023; Davidson et al., 2021; Xayachak et al., 2023). At the same time, syngas is a mature industrial vector in metallurgy, used as fuel and reductant, and it has already been evaluated in ironmaking contexts where composition affects furnace operation and productivity (Bailera, 2023).

A critical issue is that plastic waste is not a controlled feedstock. Its composition varies with collection system, sorting efficiency, product mix, additives, fillers, and contamination. This variability shifts syngas composition and increases operational instability (Forero-Franco et al., 2023; Guo et al., 2024). It also drives the formation of contaminants that are manageable in small demonstrations but difficult to handle at an industrial scale. Halogens, sulfur, and nitrogen in plastics and residues form HCl, HF, H$_2$S, NH$_3$, and metal chlorides, which constrain downstream use and impose stringent gas-cleaning requirements (Amponsah et al., 2025; de Almeida et al., 2020). Even in non-metallurgical settings, deep syngas purification is complex, multi-stage, and cost-intensive (Frilund et al., 2021). In metallurgical environments, these contaminants are more detrimental because they accelerate refractory wear, corrosion, fouling, and maintenance requirements. They also raise compliance risks in plants already operating near emissions limits.

Tar is another structural barrier. Plastic conversion produces condensable hydrocarbons, and their load depends on reactor type, temperature profile, residence time, and feed composition. Tar control is often addressed through catalytic and intensified approaches, but robustness and catalyst lifetime under real waste feeds remain unresolved (Huang et al., 2022; Mark et al., 2020). These limitations matter because metallurgy requires reliability. Blast furnace and EAF operations cannot tolerate frequent composition swings, unstable flames, or off-spec gas without clear redundancy and strong process control (Echterhof, 2021; Nielson et al., 2021).

The literature also tends to overgeneralize "syngas" as a single product. Comparative assessments show that syngas from different sources is not equivalent when evaluated for industrial use, particularly when impurities and variability are considered (Bachmann et al., 2023). In metallurgy, syngas quality is defined by strict thresholds for particulates, acid gases, alkalis, and tars, rather than solely by the H$_2$/CO ratio. Meeting these thresholds often shifts the economic balance. As a result, integration is frequently CAPEX-heavy and OPEX-intensive relative to established alternatives, including fossil syngas routes or other secondary carbon carriers already tested for metallurgical use (Afzal et al., 2023; Bashir et al., 2025; Echterhof, 2021).

Objective. This review critically assesses why plastic-derived syngas is not yet industrially viable for metallurgical applications. It focuses on constraints that dominate at the plant scale: feedstock heterogeneity, impurity formation, tar management, syngas variability, emissions control, and system economics. The analysis contrasts laboratory assumptions with metallurgical operational requirements and identifies the minimum evidence required to claim industrial readiness.

The next section outlines the methodology for selecting and evaluating the literature, with explicit inclusion criteria and a screening strategy aligned with metallurgical use cases.

Methodology

This review was conducted in accordance with the PRISMA 2020 guidelines to ensure transparency, reproducibility, and consistency in the identification, screening, and critical appraisal of the literature (Page et al., 2021). The methodology was adapted to the scope of a critical narrative review rather than a quantitative meta-analysis, with an emphasis on industrial relevance to metallurgical applications.

Literature Search Strategy

A structured literature search was conducted using Scopus, Web of Science, and Google Scholar as primary databases. The search focused on peer-reviewed journal articles, authoritative reviews, and selected industrial or government reports. Keywords and Boolean operators were used to combine terms related to plastic-derived syngas, thermochemical conversion routes, gas cleaning, contaminants, techno-economic assessment, and metallurgical use cases. Searches were limited to English-language publications.

The temporal window spanned 2010 to 2025, with priority given to studies published after 2020 due to rapid advances in plastic waste valorization and decarbonization strategies. Reference lists of key review papers were also manually screened to identify additional relevant studies.

Eligibility and Screening Criteria

After duplicate removal, titles and abstracts were screened against predefined inclusion and exclusion criteria. Studies were included if they met at least one of the following criteria:

- Addressed pyrolysis or gasification of plastic waste, with syngas as a primary product;
- Reported syngas composition, contaminants, tar formation, or gas cleaning requirements.
- Evaluated techno-economic, life-cycle, or scale-up aspects.
- Discussed integrating syngas into industrial or metallurgical processes.

Studies were excluded if they were limited to laboratory proof-of-concept without relevance to scale-up, focused exclusively on polymer chemistry without syngas production, or addressed energy applications without transferable insights for metallurgical environments.

Full-text screening was then conducted to assess methodological rigor and relevance to industrial constraints. Disagreements during screening were resolved through critical reassessment of scope alignment.

Figure 1 summarizes the systematic literature search and selection process for this review, following the PRISMA 2020 framework. The diagram outlines the identification of records from major scientific databases and additional sources, the screening and eligibility steps, and the criteria for full-text exclusion, culminating in the final set of studies analyzed.
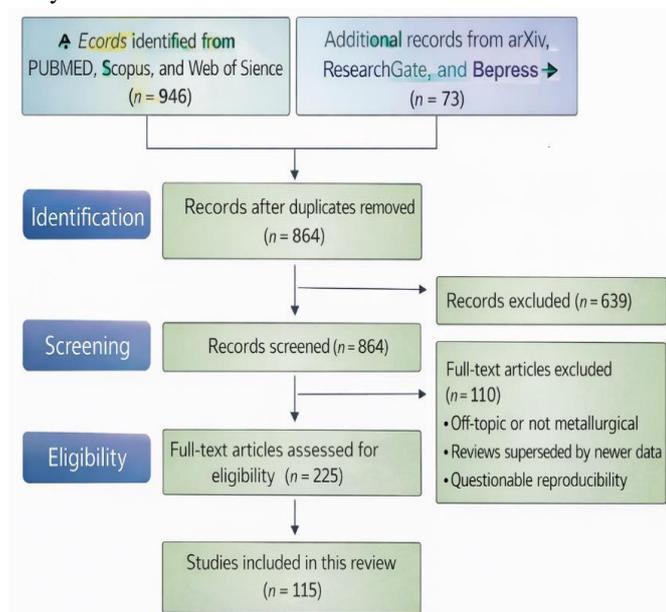
Figure 1: PRISMA 2020 flow diagram. Adapted from Page et al. (2021).

Study Classification and Critical Evaluation

The final corpus comprised 115 references, consolidated in the final version of the article. These studies were grouped thematically: (i) plastic waste conversion technologies; (ii) syngas composition and variability; (iii) contaminant formation and gas cleaning; (iv) metallurgical integration and operational constraints; and (v) techno-economic and environmental assessments.

Instead of aggregating results statistically, each study was evaluated qualitatively for industrial feasibility, operational robustness, and compatibility with metallurgical process requirements. Particular attention was given to discrepancies between laboratory-scale assumptions and large-scale operational realities.

This critical synthesis approach enabled the identification of structural barriers and recurring limitations that explain the absence of industrial deployment of plastic-derived syngas in metallurgy.

Scope Limitations

This review does not aim to exhaustively quantify emissions or costs across all reported systems. Instead, it prioritizes comparability, process realism, and industrial constraints. Pilot-scale demonstrations and studies explicitly addressing metallurgical integration were given greater weight than laboratory-only investigations.

What Syngas from Plastic Recycling Actually Is

The term syngas from plastic recycling is often used as if it referred to a single, well-defined industrial product. It does not. In practice, it describes a broad family of gases with highly variable composition, contaminant load, and thermochemical behavior. This section clarifies what plastic-derived syngas is, why its properties fluctuate, and why this variability conflicts with metallurgical requirements.

Feedstock Heterogeneity

Plastic waste is not a uniform raw material. Post-consumer streams typically contain mixtures of polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET), with proportions that vary by region, collection system, and sorting efficiency (Kaminsky, 2021; Hinton et al., 2022). Each polymer decomposes differently and produces distinct gas species during thermochemical conversion.

Beyond the polymer matrix, additives are the primary concern. Plastic products contain plasticizers, stabilizers, flame retardants, pigments, fillers, and reinforcing agents. Common additives include calcium carbonate, silica, alumina, antimony oxides, and halogenated compounds (Mark et al., 2020; Ma et al., 2024). During conversion, these components form inorganic vapors, fine particulates, and corrosive gases that directly affect syngas usability.

Contamination further amplifies variability. Food residues, paper, textiles, metals, and dirt enter the feed even after sorting. Chlorine content may vary by an order of magnitude depending on the PVC fraction or residual salts (Weiland et

al., 2021; Koritár & Haydary, 2025). From a metallurgical standpoint, this means syngas quality is feedstock-driven rather than process-controlled.

Table 1 summarizes typical polymer types, dominant decomposition products, and critical contaminants relevant to metallurgy.

Table 1. Major plastic polymers, typical additives, and critical contaminants affecting syngas quality for metallurgy. Adapted from Mark et al. (2020), Ma et al. (2024), and Weiland et al. (2021).

Polymer	Typical applications	Common additives and fillers	Main contaminants released during conversion	Metallurgical relevance/impact
PE (Polyethylene)	Packaging films, bottles, containers	Antioxidants, slip agents, $CaCO_3$ fillers, pigments	Light hydrocarbons, waxes, tar precursors	Tar formation; fouling of burners and gas lines
PP (Polypropylene)	Automotive parts, packaging, textiles	Stabilizers, pigments, $CaCO_3$, talc	Olefins, heavy hydrocarbons, soot	Tar condensation; flame instability
PS (Polystyrene)	Disposable packaging, insulation foams	Flame retardants, dyes, residual styrene	Aromatics, polycyclic hydrocarbons	High tar load; catalyst deactivation
PVC (Polyvinyl chloride)	Pipes, cables, flooring	Plasticizers (phthalates), stabilizers (Pb, Zn), fillers	HCl, metal chlorides, chlorinated organics	Severe corrosion; refractory degradation; PCDD/F risk
PET (Polyethylene terephthalate)	Beverage bottles, fibers	Antimony catalysts, colorants, fillers	CO_2, oxygenates, fine particulates	Syngas dilution; reduced reducing potential
Mixedplastics	Municipal waste streams	Combination of above + contaminants (paper, food, salts)	HCl, H_2S, NH_3, alkalis, tar, particulates	Unstable syngas; complex gas cleaning requires

The key challenge is not the polymer backbone itself but the additive and contaminant package associated with real-world plastic waste streams. From a metallurgical perspective, chlorine-bearing species, alkalis, heavy aromatics, and fine particulates are decisive, as they directly affect refractory integrity, tuyere performance, and emission control systems. This complexity explains why plastic-derived syngas cannot be treated as compositionally equivalent to conventional metallurgical syngas, even when produced under controlled reactor conditions.

Production Routes

Plastic-derived syngas is produced primarily through pyrolysis or gasification, sometimes in staged or hybrid configurations. Pyrolysis operates under oxygen-free conditions and prioritizes the formation of liquids and waxes, with gas as a secondary product. Gasification introduces oxidants such as air, oxygen, steam, or CO_2 to favor gas production (Al-Qadri et al., 2024; Shah et al., 2023).

The route is important because it determines gas stability. The composition of pyrolysis gas strongly depends on temperature ramps, residence time, and secondary cracking efficiency. Gasification adds further variability through oxidant dilution and incomplete conversion (Halba et al., 2022; Qi et al., 2025). Air-blown systems introduce large nitrogen fractions. Steam and CO_2 shift equilibrium but reduce the effective heating value.

Across studies, extreme variability in the H_2/CO ratio, total combustible fraction, and inert dilution is consistently reported, even under nominally similar conditions (Forero-Franco et al., 2023; Tian et al., 2024). This variability is

manageable in batch experiments but problematic in continuous metallurgical operations.

The fundamental source of variability in plastic-derived syngas is the thermochemical conversion route employed (Figure 2). Pyrolysis and gasification differ not only in reactor configuration and operating conditions but also in the presence of an oxidant, conversion extent, and by-product formation. These differences directly control syngas composition, dilution level, and stability, which are decisive parameters for metallurgical applicability.
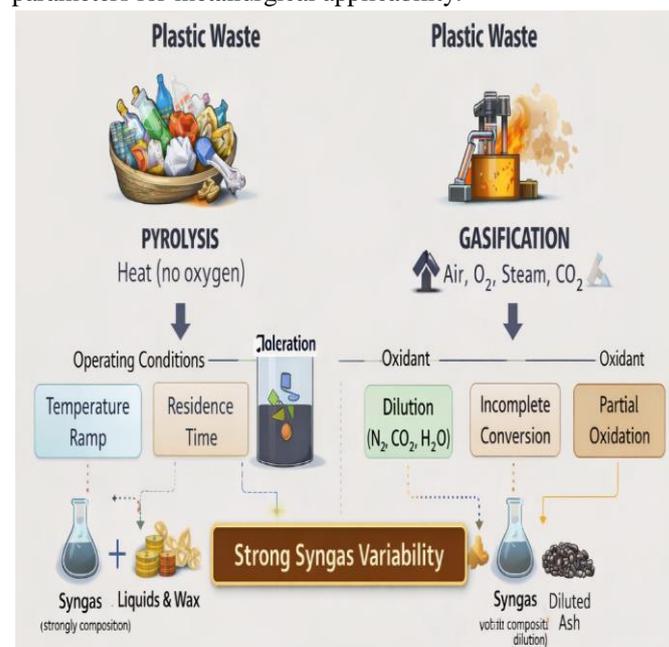
Figure 2: Simplified comparison between plastic pyrolysis and gasification routes. Adapted from Kaminsky (2021), Halba et al. (2022), and Shah et al. (2023).

The figure shows that syngas variability is not a secondary operational issue but an intrinsic consequence of the conversion route. While pyrolysis may yield higher concentrations of CO and H_2, it also produces liquids, waxes, and heavy hydrocarbons that complicate downstream use. Gasification suppresses condensables but introduces systematic dilution and oxidant-dependent instability. From a metallurgical standpoint, neither route inherently delivers a stable, high-reducing-potential syngas without extensive conditioning, underscoring the need to distinguish laboratory syngas characterization from industrially relevant gas quality.

Typical Syngas Composition Vs Metallurgical Needs

Metallurgical processes impose strict constraints on reducing potential, flame stability, and impurity levels. Plastic-derived syngas rarely meets these constraints without extensive conditioning. Reported compositions often show strong dilution by CO_2, N_2, and H_2O, particularly in air- or steam-assisted systems (Guo et al., 2024; Piemsinlapakunchon & Paul, 2021).

From a reduction perspective, dilution lowers the partial pressures of CO and H_2. This directly reduces the chemical driving force for iron oxide reduction and limits thermal efficiency in burners and tuyeres (Bailera, 2023; Nielson et al., 2021). Even when nominal H_2/CO ratios appear suitable, the absolute reducing capacity is often insufficient due to inert ballast.

Contaminants further restrict use. Acid gases, alkalis, and trace amounts of tar, which are acceptable for power generation, become unacceptable in metallurgical furnaces, where they promote corrosion, clogging, and refractory degradation (Rahim et al., 2023; Marcantonio et al., 2021). As a result, the "syngas" discussed in recycling studies is chemically and operationally distinct from syngas designed for metallurgical duty.

Table 2 shows that plastic-derived syngas rarely meets metallurgical requirements without extensive conditioning. Even when H_2/CO ratios appear acceptable, dilution by CO_2, N_2, and H_2O significantly reduces the effective reducing partial pressure. In metallurgical reactors, chemical potential and stability matter more than nominal composition. The impurity levels in plastic-derived syngas exceed acceptable thresholds by one to three orders of magnitude, explaining the lack of industrial adoption despite favorable laboratory results.

Table 2. Comparison between reported plastic-derived syngas compositions and typical metallurgical syngas requirements. Adapted from Nielson et al. (2021), Rahim et al. (2023), and Marcantonio et al. (2021).

Parameter	Plastic-derived syngas (typical range)	Metallurgical syngas requirement	Critical implication for metallurgy
H_2 (vol%)	10–40	30–60	Often insufficient reducing capacity when diluted
CO (vol%)	10–35	30–50	Low CO partial pressure limits iron oxide reduction
H_2/CO ratio	0.5–2.5	Process-specific, butstable	Ratio alone is misleading without absolute pressure
CO_2 (vol%)	15–40	<10	Strong dilution; shifts equilibrium against reduction
N_2 (vol%)	10–50 (air gasification)	<5	Inert ballast; lowers flame temperature
H_2O (vol%)	5–20	As low as possible	Reduces effective reducing potential
Lower heating value (MJ/Nm³)	4–12	>10–12	Often marginal for burners and tuyeres
Tar (mg/Nm³)	100–10,000	<50–100	Fouling; blockage; unstable operation
HCl (ppm)	10–3,000	<1–5	Sever ecorrosion; refractory attack
H_2S (ppm)	5–1,000	<1–10	Catalyst poisoning; SO_2 emissions
Alkalis (Na, K, mg/Nm³)	10–200	<1	Slagging; refractory degradation
Particulates (mg/Nm³)	50–5,000	<5–10	Erosion; deposition; filter overload
Pressure stability	Fluctuating	Stable	Process control and safety risk

Even when plastic-derived syngas contains nominally sufficient CO and H_2, its effective reducing capacity is strongly constrained by dilution (Figure 3). The presence of CO_2, N_2, and H_2O lowers the partial pressure of the active reducing species and weakens the chemical driving force for metal oxide reduction, particularly under atmospheric or slightly pressurized conditions typical of many metallurgical units.
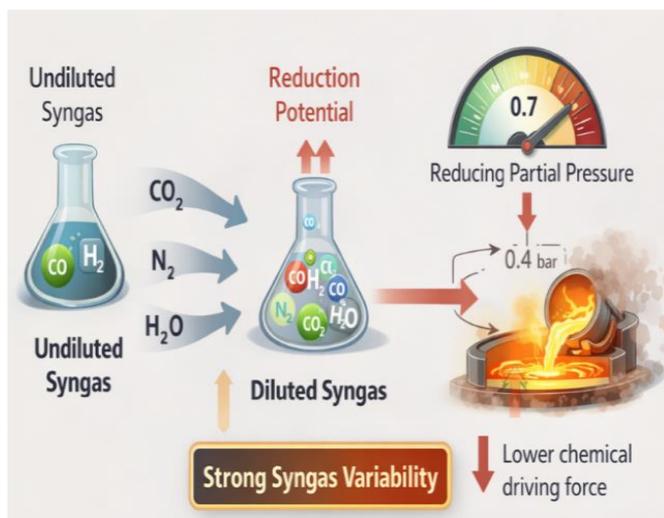
Figure 3: Conceptual illustration of syngas dilution by CO_2, N_2, and H_2O and its effect on reducing partial pressure in metallurgical applications. Adapted from Bailera (2023) and Guo et al. (2024).

The figure shows that metallurgical performance depends on the partial pressure of reducing gases rather than on the bulk syngas composition alone. Diluted syngas streams exhibit lower reaction rates, require longer residence times, and are more sensitive to fluctuations in gas composition. As a result, syngas that is thermodynamically viable on a compositional basis may still be operationally inadequate for metallurgical reduction, particularly in processes designed around concentrated fossil-based reductants.

The intrinsic variability described in this section is not a secondary issue. It defines the technical limits of plastic-derived syngas. The next section examines how this variability translates into contaminant formation, gas-cleaning complexity, and operational risk, all of which ultimately determine industrial viability.

Thermodynamics Is Not the Bottleneck

Syngas is a valid reductant on paper. That is not the debate. The debate is whether plastic-derived syngas can deliver the required reducing potential at the required rate with a stable composition within metallurgical hardware. Most studies confirm feasibility at equilibrium. Few demonstrate robustness under industrial constraints (Tang et al., 2020; Zhang et al., 2022).

Reduction Reactions (MO–CO / MO–H₂)

For iron oxides and several base-metal oxides, reduction by CO and/or H_2 is thermodynamically feasible across wide temperature ranges. Equilibrium calculations and classical metallurgy literature support this. The reaction families are well known:

- $MO + CO \rightarrow M + CO_2$
- $MO + H_2 \rightarrow M + H_2O$

Table 3 summarizes representative equilibrium conditions for MO–CO and MO–H_2 reduction and highlights the temperature dependence of reducing potential.

Table 3. Representative equilibrium conditions for MO–CO and MO–H_2 reduction reactions and temperature dependence of reducing potential. Adapted from Tang et al. (2020), Zhang et al. (2022), and Yi et al. (2022)

Metal oxide (MO)	Reduction reaction	Thermodynamically feasible temperature range (°C)	Dominant controlling parameter	Commenton industrial relevance
$Fe_2O_3 \rightarrow Fe_3O_4$	$Fe_2O_3 + CO \rightarrow Fe_3O_4 + CO_2$	> 300	CO/CO_2 ratio	Easily feasible; rarely limiting
	$Fe_2O_3 + H_2 \rightarrow Fe_3O_4 + H_2O$	> 250	H_2/H_2O ratio	Highly favorable at low T
$Fe_3O_4 \rightarrow FeO$	$Fe_3O_4 + CO \rightarrow 3FeO + CO_2$	> 600	CO partial pressure	Sensitive to dilution
	$Fe_3O_4 + H_2 \rightarrow 3FeO + H_2O$	> 550	H_2 partial pressure	Affected by H_2O buildup
$FeO \rightarrow Fe$	$FeO + CO \rightarrow Fe + CO_2$	> 700–750	Effective CO pressure	Strongly impacted by CO_2, N_2
	$FeO + H_2 \rightarrow Fe + H_2O$	> 650–700	H_2/H_2O ratio	Requires dry gas
$MnO \rightarrow Mn$	$MnO + CO \rightarrow Mn + CO_2$	> 1200	CO activity	Marginal even with pure gas
	$MnO + H_2 \rightarrow Mn + H_2O$	> 1150	H_2 activity	Rarely practical
$Cr_2O_3 \rightarrow Cr$	$Cr_2O_3 + 3CO \rightarrow 2Cr + 3CO_2$	> 1300	CO pressure	Gas reduction impractical
	$Cr_2O_3 + 3H_2 \rightarrow 2Cr + 3H_2O$	> 1250	H_2 purity	Kinetically prohibitive

Reduction is thermodynamically allowed for iron oxides and several base-metal oxides. However, feasibility at equilibrium does not imply process viability. Reaction rates, gas composition, and contact efficiency remain unaddressed at this level of analysis.

The same logic underpins hydrogen metallurgy and syngas-based reduction (Tang et al., 2020; Xionggang et al., 2022). In addition, coupled reactions, such as the water–gas shift and the Boudouard equilibrium, shape the effective reducing atmosphere:

- $CO + H_2O \rightleftharpoons CO_2 + H_2$
- $2CO \rightleftharpoons CO_2 + C$

These equilibria can either help or hinder reduction, depending on temperature and gas composition. They are often favorable in idealized cases but become less favorable when the gas is diluted and unstable (Etminan et al., 2025; Lee et al., 2025).

Where the literature overreaches: feasibility is sometimes treated as sufficient evidence to adopt a process. It is not. Metallurgy is not an equilibrium experiment.

Why Are Ellingham Diagrams Misleading Alone

Ellingham diagrams are useful. They are also routinely misused in this topic. They indicate *possibility*, not *performance*.

Figure 4 shows that thermodynamic feasibility is often assessed using Ellingham diagrams, which relate oxide stability to temperature under idealized equilibrium conditions. While useful as a first-order screening tool, these diagrams implicitly assume the presence of concentrated reducing agents, a stable gas composition, and effective gas–solid contact. These assumptions are rarely satisfied when applied to plastic-derived syngas.
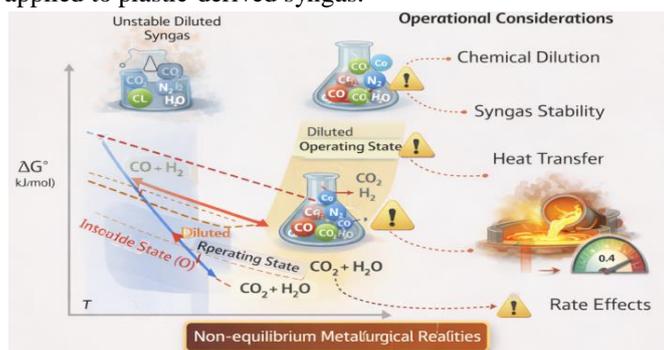
Figure 4: Conceptual limitations of Ellingham diagrams when applied to diluted and unstable syngas streams. Adapted from Tang et al. (2020) and Podyacheva et al. (2022).

The figure illustrates that Ellingham diagrams alone cannot capture the operational reality of metallurgical reduction using plastic-derived syngas. Dilution by CO_2, N_2, and H_2O reduces the effective reducing potential, while instability in gas composition introduces kinetic and mass-transfer penalties absent from equilibrium analysis. As a result, reductions predicted as "thermodynamically feasible" may remain rate-limited or operationally impractical, underscoring that thermodynamics is not the controlling bottleneck in this context.

Three blind spots matter here:

(i) Kinetics and gas–solid contact are missing

Industrial reduction depends on interfacial reaction rates, pore diffusion, and product-layer transport. A "thermodynamically allowed" reaction can still be too slow or incomplete within realistic residence times (Ogbezode et al., 2023; Yi et al., 2022). This is why

process intensification and reactor design, not only $\Delta G°$, govern outcomes (Cheng et al., 2025).25).

(ii) Dilution destroys partial pressure

Plastic-derived syngas is commonly diluted with CO_2, N_2, and H_2O. Ellingham diagrams do not show this directly. Reduction depends on effective pCO and pH2, not nominal "syngas present." When inerts dominate, reducing potential collapses even if H_2/CO appears acceptable (Zhang et al., 2022; Podyacheva et al., 2022).

(iii) Mass transfer and mixing are ignored

Real furnaces have gradients. Jets, tuyeres, and boundary layers control what the solid "sees." CFD and process studies show that injection strategy and flow fields can limit the local reducing atmosphere, even with a good bulk composition (Wang, Q., et al., 2023; Dong et al., 2021). That is a first-order constraint in blast furnaces and other high-throughput reactors.

In short, Ellingham diagrams serve as the starting point for the discussion. They are not a screening tool for industrial viability.

Key Message

If thermodynamics were sufficient, syngas would already be in use.

The industry already has access to syngas routes and uses them where they are stable and cost-effective. The barrier for plastic-derived syngas is not "can CO and H_2 reduce oxides?" The barrier is "can this specific gas, from this feedstock, be delivered cleanly and consistently at scale?" (Mohammad & Harichandan, 2023; Liu et al., 2024; Koppala et al., 2025).

Figure 5 shows that the limitations of equilibrium-based assessments become even more evident when the gap between thermodynamic predictions and industrial operations is taken into account. Real-world metallurgical environments are governed by reaction kinetics, gas–solid contact efficiency, and transient operating conditions, which equilibrium diagrams alone cannot capture. This mismatch is particularly pronounced when dilute and unstable syngas streams are used as reducing agents.
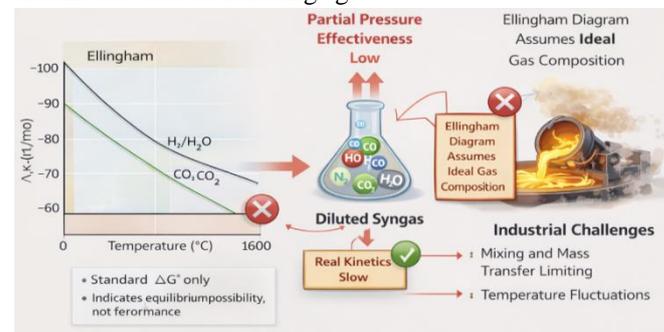
Figure 5: Comparison between equilibrium-based reduction assumptions and real industrial reduction environments, highlighting the role of kinetics and mass transfer. Adapted from Tang et al. (2020), Podyacheva et al. (2022), Nielson et al. (2021), and Wang, Q. et al. (2023).

The figure illustrates that equilibrium feasibility does not translate into operational robustness. In practice, diluted syngas streams exhibit slower reduction rates and higher sensitivity to mixing, residence time, and thermal stability. As a result, systems designed around equilibrium assumptions often fail to deliver consistent metallurgical performance when supplied with plastic-derived syngas, reinforcing that kinetics and mass transfer—not thermodynamics—govern industrial viability.

Once thermodynamics is properly placed, the true bottlenecks become unavoidable. The next section focuses on the cleaning of contaminants, tar, and gas. These constraints drive reliability, emissions compliance, corrosion risk, and cost.

The Real Bottlenecks: What Is Missing

Plastic-derived syngas fails in metallurgy for practical reasons, not theoretical ones. The missing pieces are quality control, contaminant management, rate control (kinetics/transport), and plant-level integration. These gaps are structural. They do not disappear by demonstrating equilibrium feasibility.

Syngas Quality Control

Plastic waste conversion does not produce a stable "commodity gas." Instead, it produces a gas whose composition shifts with feedstock mix, moisture, reactor hydrodynamics, oxidant choice, and transient operation. That variability is not a nuisance. It drives furnace instability and forces the adoption of conservative operating envelopes (Madanikashani et al., 2022; Xu & Shi, 2022).

Most papers report H_2/CO, but that is not a specification. Metallurgy requires a metal-grade syngas definition that sets limits on inert dilution, acid-gas content, alkali carryover, particulate matter, and tar. Without an explicit target, "improvement" has no meaning, and scale-up remains unbounded in risk and cost (Gupta et al., 2023; Tomić et al., 2024).

Table 4 presents a proposed metal-grade syngas specification template and highlights which parameters are typically omitted from plastic-syngas studies.

Table 4. Proposed template for a "metal-grade syngas" specification and common reporting gaps in plastic-derived syngas studies. Adapted from Gupta et al. (2023), Tomić et al. (2024), and Lewis et al. (2022).

Parameter category	Specification required for metallurgy	Typical reporting in plastic-syngas studies	Critical gap / implication
Major components	H_2, CO, CO_2, N_2, H_2O (vol%, dry & wet basis)	Often H_2/CO only	Absolute reducing capacity not assessed
H_2/CO ratio	Stable and process-specific	Reported as average	Temporal variability ignored
Inertdilution	$CO_2 + N_2$ typically<15–20 vol%	20–60 vol% common	Reduced flame temperature and driving force
Lower heating value	≥10–12 MJ/Nm³	Sometimes reported	Burner and tuyere compatibility unclear
Pressure & temperature	Defined delivery window	Rarely specified	Integration assumptions unverifiable
Tar	<50–100 mg/Nm³ (hot gas)	Reported inconsistently or omitted	Fouling and instability risk underestimated
Particulates	<5–10 mg/Nm³	Often vomitted	Erosion and deposition risk
Chlorine (HCl, Cl_2)	<1–5 ppm	10–1000+ ppm reported	Corrosion and refractory attack
Sulfur (H_2S, COS)	<1–10 ppm	10–1000 ppm common	Catalyst poisoning; Sox burden
Alkalis (Na, K)	<1 mg/Nm³	Rarely measured	Slagging and refractory damage
Nitrogen species (NH_3, HCN)	Defined limits	Usually omitted	NOx formation and redox instability
Trace metals	Defined thresholds	Not reported	Accumulation in loops
Gas stability	Short- and long-term fluctuation limits	Single-point analysis	Control strategy undefined
Sampling basis	Standardized (ISO, hot/cold)	Non-uniform methods	Data not comparable
Cleanup efficiency	Removal efficiency per contaminant	Global "gas cleaning" claim	CAPEX/OPEX opaque
Availability /uptime	≥95% target	Not discussed	Economic viability unaddressed

This comparison makes clear that most plastic-derived syngas studies cannot be evaluated against metallurgical requirements. Reporting practices emphasize indicative compositional metrics rather than operability and risk. Without a metal-grade specification, claims of "suitable syngas" remain qualitative and non-transferable to industrial design. This is a red flag for industrial claims (Tomić et al., 2024; Lewis et al., 2022).22).

Contaminants Incompatible with Metallurgy

Metallurgy is intolerant of contaminants that many waste-to-syngas studies consider "manageable." The issue is not only emissions but also corrosion, refractory attack, deposition, catalyst poisoning (where applicable), and unplanned downtime.

Chlorine (HCl, Cl₂, Metal Chlorides)

Chlorine-rich feeds and mixed plastics can generate HCl and volatile chlorides. Even low concentrations matter in hot sections and off-gas systems. Chlorides accelerate high-temperature corrosion and can destabilize downstream loops (Sahraei et al., 2020; Gupta et al., 2023). Routes such as SCWG and advanced concepts do not eliminate the need to manage halogens; they shift the problem to different unit operations (Ciuffi et al., 2020).

Sulfur (H₂S, COS). Sulfur species impose strict limits because they poison catalysts (if used), increase SOx control burdens, and interact with metal surfaces at high temperatures. Removal is possible but adds cost and complexity and often requires multi-step systems (Martinez et al., 2025; Gupta et al., 2023).

Tar and Heavy Hydrocarbons

Tar is not "just an efficiency penalty." In metallurgical integration, it is an operability issue. Tar condenses, fouls, and causes unstable combustion. The cleanup requirement is severe and persistent, especially under variable feed conditions (Madanikashani et al., 2022; Tomić et al., 2024). Even if downstream syngas conversion is not the goal, tar removal remains mandatory for reliable delivery (Khalid et al., 2024).

Figure 6 summarizes the main contaminant families in plastic-derived syngas and why they are structurally incompatible with metallurgical duty.
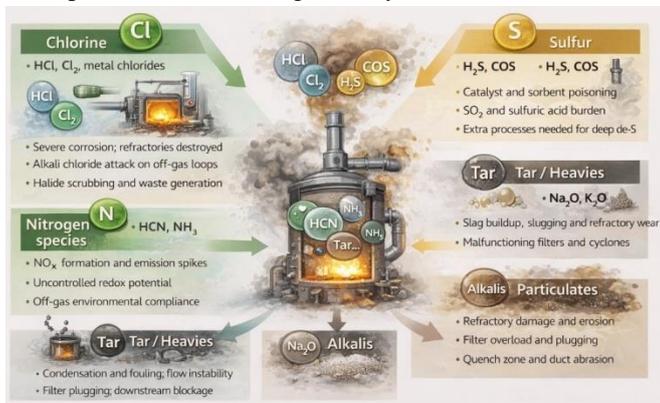
Figure 6: Major contaminant families in plastic-derived syngas and their primary failure modes in metallurgical applications. Adapted from Ciuffi et al. (2020), Sahraei et al. (2020), Marcantonio et al. (2021), and Martinez et al. (2025).

The key point is that contaminant control must be designed for worst-case feed and transient operation. That is expensive. It also reduces availability, which dominates economics in real plants (Lewis et al., 2022; Tomić et al., 2024).

Kinetics and Mass Transfer

Even if the gas were clean, the reduction rate still matters. Metallurgical reactors are rate-driven. Residence time is constrained. Gas–solid contact is imperfect. Local partial pressures rarely equal the bulk composition.

Gas–Solid Limits (Pyrometallurgy)

Reduction rates depend on interfacial kinetics, pore diffusion, and product-layer formation. Diluted syngas lowers the effective driving force and increases the time required to reach a given metallization level, creating a residence-time mismatch with existing furnace practice (Madanikashani et al., 2022; Xu & Shi, 2022).

Gas–Liquid Limits (Hydrometallurgy)

When syngas is proposed as a reductant or reagent precursor in solution-phase systems, gas–liquid transfer and bubble hydrodynamics become limiting factors. Variability in composition leads to unstable redox control and inconsistent reaction endpoints (Khalid et al., 2024; Lewis et al., 2022).

Figure 7 contrasts equilibrium "allowed" reduction with rate-limited reduction under diluted, transient syngas, highlighting the residence-time mismatch.
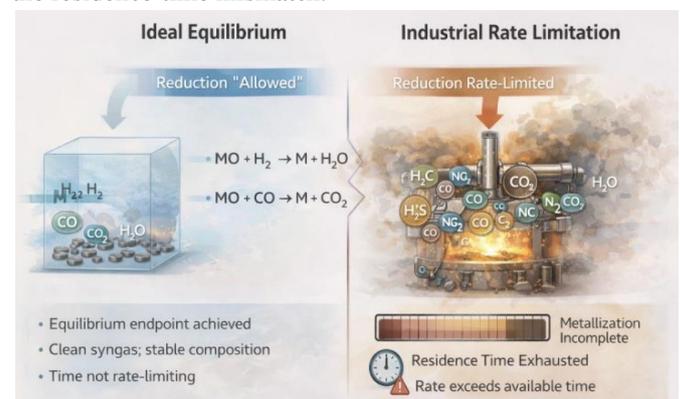
Figure 7: Conceptual comparison between equilibrium-based reduction assumptions and real industrial reduction environments. Adapted from Madanikashani et al. (2022) and Xu & Shi (2022).

Rate limitations are why thermodynamic feasibility does not translate into operational feasibility. Industrial processes are designed around throughput and control, not equilibrium endpoints.

Process Integration Failures

Most integration proposals fail at the plant level. They assume syngas can be "dropped into" existing furnaces, a weak assumption.

Furnaces Are Not Designed to Operate on Diluted Syngas

High inert content reduces flame temperature and alters heat transfer. It can require higher flow rates to deliver the same heat, thereby increasing the pressure drop and off-gas volume. This cascades into larger ductwork, fans, filters, and scrubbers (Xu & Shi, 2022; Lewis et al., 2022).

Off-Gas Loops Are Not Compatible

Closed-loop concepts often overlook contaminant accumulation and purge requirements. Chlorides and sulfur do not vanish. They accumulate in loops unless deliberately

removed, which reintroduces waste streams and compliance challenges (Sahraei et al., 2020; Ciuffi et al., 2020).

No Integrated Redox Control

Metallurgical viability requires tight redox control across burners, reactors, and off-gas handling. With variable syngas, redox control becomes a multi-variable problem that current proposals rarely address with credible instrumentation and control strategies (Madanikashani et al., 2022; Tomić et al., 2024).

Figure 8 maps the integration points where plastic-derived syngas typically fails: quality control, cleanup, delivery, and loop closure.

Figure 8: Typical integration failure points for plastic-derived syngas in metallurgical plants, spanning feedstock quality, gas cleanup, delivery, and process loop closure. Adapted from Tomić et al. (2024) and Lewis et al. (2022).

This is why "working at pilot scale" is insufficient. Industrial integration must be proven as a system, with uptime, purge logic, and compliance built in.

The bottlenecks above do not mean plastic-derived syngas is impossible everywhere. They mean it is not a universal solution. The next section narrows the discussion to metal-specific viability and poses a more precise question: where, if anywhere, could it work with realistic cleanup and control?

Metal-Specific Viability: Where It Might Work

Plastic-derived syngas is not universally unsuitable. Its limitations depend strongly on the metal system, reaction pathway, and process role. This section distinguishes realistic opportunities from marginal cases and from metals for which application is not credible under current conditions.

To avoid generalization, the viability of plastic-derived syngas must be evaluated on a metal-by-metal basis, considering oxide stability, reaction pathway, impurity tolerance, and process role. Table 5 summarizes the assessment.

Table 5. Metal-specific viability of plastic-derived syngas in metallurgical applications. Adapted from Tang et al. (2020), Nielson et al. (2021), Safavi & Richter (2021), and Okolie et al. (2021).

Metal	Typical oxide stability	Role of syngas	Tolerance to dilution & contaminants	Industrial viability (today)	Key limitation
Cu	Low	Slag cleaning, secondary reduction	Moderate–high	Realistic	Gas quality consistency
Pb	Low	Secondary smelting, fuel/reductant	High	Realistic	Emissions control
Sn	Low	Residue reduction	High	Realistic	Tar management
Fe	Moderate	Pre-reduction only	Low	Marginal/conditional	Residence time, dilution
Zn	Moderate (volatile metal)	Coupled reduction–volatilization	Low–moderate	Conditional	Cl/S interference
Cr	Very high	—	Very low	Not realistic	Thermodynamics + kinetics
Ti	Very high	—	Very low	Not realistic	Oxygen affinity
Al	Extremely high	—	Very low	Not realistic	Competes poorly with electrolysis

Viability is narrow and highly context-dependent. Plastic-derived syngas may support secondary metallurgy and residue treatment, but it fails when required to control primary reduction pathways or to operate within tightly balanced redox systems.ems.

Metals with Realistic Potential

Copper (Cu), lead (Pb), and tin (Sn) are the most plausible entry points. These systems share three favorable characteristics: relatively low oxygen affinity, tolerance to moderate gas dilution, and frequent operation in secondary or residue-processing contexts.

In secondary copper metallurgy, syngas can serve as a supplementary reductant or fuel for slag cleaning and residue treatment, where absolute reduction rates are less critical and residence times are longer (Wang et al., 2020; Dong et al., 2021). Plastic-derived syngas need not drive primary smelting. It can help reduce Cu_2O in slags or residues where equilibrium margins are wide, and impurity tolerance is higher.

Lead and tin systems are even more forgiving. Reduction of PbO and SnO occurs at relatively low temperatures and with modest reducing potential. In rotary furnaces and secondary

recovery units, syngas quality requirements are less stringent than in ironmaking, and intermittent operation is common (Ogbezode et al., 2023; Safavi & Richter, 2021). In these contexts, plastic-derived syngas may replace part of the fossil fuel input without controlling the entire redox balance.

Importantly, these applications do not require closed-loop gas reuse or high-purity syngas. They rely on open-loop operation, limited refractory exposure, and downstream gas treatment already sized for contaminated streams (Yi et al., 2022; Tang et al., 2020).

Marginal or Conditional Cases

Iron (Fe) occupies an intermediate position. Thermodynamically, reduction by CO and H_2 is well established. However, industrially, plastic-derived syngas fails to meet the requirements of blast furnaces, shaft furnaces, or fluidized beds when used as a primary reductant.

The only realistic role for Fe today is as a pre-reduction agent. Low degrees of metallization, such as $Fe_2O_3 \rightarrow Fe_3O_4$ or partial $Fe_3O_4 \rightarrow FeO$ conversion, may be achieved upstream of the main reactor (Nielson et al., 2021; Mohammad et al., 2023). Even so, strict limits apply. Gas dilution, variability, and contaminants constrain achievable reduction levels and complicate integration.

Zinc (Zn) is a special case. Reduction is coupled with volatilization. In theory, syngas could support carbothermic or mixed-gas reduction of ZnO, followed by vapor recovery (Chuayboon & Abanades, 2021; Bellouard et al., 2020). In practice, however, chloride and sulfur contamination strongly interfere with Zn vapor condensation and recovery. Process windows are narrow, and impurity control becomes dominant (Maric et al., 2020; Safavi et al., 2022). As a result, viability remains conditional and highly site-specific.

Metals Where It Is Not Realistic (Today)

For chromium (Cr), titanium (Ti), and aluminum (Al), plastic-derived syngas is not a viable reductant with current technology.

These metals form highly stable oxides that require either extremely low oxygen potentials or electrochemical methods. Gas-phase reduction is kinetically slow and thermodynamically unfavorable unless unrealistically high CO or H_2 activities are maintained (Tang et al., 2020; Zhang et al., 2022). Diluted, transient syngas cannot meet these conditions.

In addition, these processes are highly sensitive to impurities. Chlorides, sulfur, alkalis, and particulates are incompatible with Cr, Ti, and Al processing routes. For aluminum, any carbonaceous gas route performs poorly compared with established electrolytic pathways and poses unacceptable contamination risks (Xionggang et al., 2022; Okolie et al., 2021).

Claims of the broad applicability of plastic-derived syngas to these metals rely almost exclusively on equilibrium arguments or laboratory-scale demonstrations. No credible industrial pathway exists at present.

The analysis above shows that plastic-derived syngas is not a universal metallurgical solution. Its viability is limited and conditional. The next section examines a recurring pattern in the literature and in practice: why industrial trials rarely progress beyond pilot scale, even in systems where thermodynamics and metal selection appear favorable.

Why Industrial Trials Rarely Progress

Industrial trials with plastic-derived syngas rarely fail due to a single flaw. They stall because technical, economic, and regulatory risks accumulate faster than they can be mitigated. This section explains why pilot success almost never translates into sustained industrial operation.
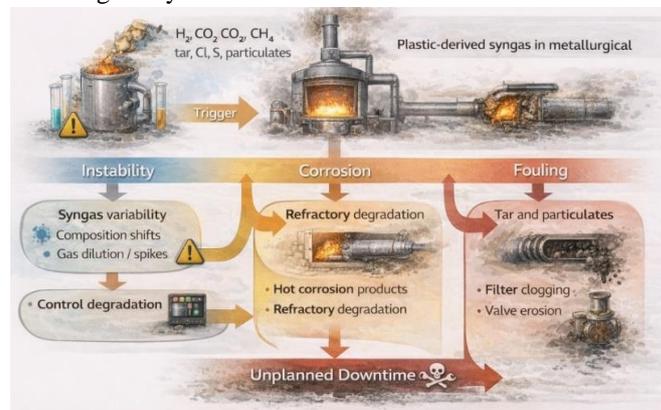
Technical Risk

Plastic-derived syngas introduces instability at multiple levels. Its composition fluctuates with the feedstock mix, operating regime, and transient events. Furnaces and reactors are not designed to handle this variability. Control systems struggle to compensate in real time, particularly when gas quality changes faster than residence times allow (Zhang et al., 2021; Guo et al., 2024).

Corrosion and fouling are persistent. Chlorides attack refractories and metallic components. Tar and fine particulates foul burners, valves, and heat exchangers. These effects are cumulative. Short pilot campaigns rarely reveal them. Continuous operation does (Maric et al., 2020; Safavi et al., 2022).

Unplanned downtime becomes frequent. Maintenance intervals shorten. Availability falls below the thresholds required for metallurgical economics. At this point, trials are usually discontinued rather than optimized (Tomić et al., 2024).

Figure 9 summarizes the dominant technical failure modes observed when syngas derived from plastic is introduced into metallurgical systems.

Figure 9: Dominant technical failure modes observed during the introduction of plastic-derived syngas into metallurgical systems. Adapted from Ciuffi et al. (2020), Sahraei et al. (2020), Tomić et al. (2024), and Lewis et al. (2022).

Figure 9 shows that failure is rarely abrupt. It is progressive, driven by instability, corrosion, and fouling that exceed design margins.

Economic Risk

Even when technical feasibility is present, economics dominates outcomes. Plastic-derived syngas requires extensive gas cleaning. Removal of tar, particulates, HCl, H_2S, alkalis, and trace metals requires multi-stage systems. These units are capital-intensive and scale poorly at small and medium capacities (Kulas et al., 2023; Tomić et al., 2024).

Operating costs are equally problematic. Sorbents, scrubbing chemicals, wastewater treatment, residue disposal, and frequent maintenance add up. On a delivered-energy or delivered-reduction basis, plastic-derived syngas struggles to compete with coke, coal, or natural gas, even before accounting for reliability penalties (Lewis et al., 2022; Kang et al., 2025).

In numerous trials, the primary cost factor is gas conditioning rather than syngas itself. When the full cleanup is accounted for, the economic justification is undermined (Tomić et al., 2024; Kulas et al., 2023).

Table 6 compares the primary CAPEX and OPEX contributors for integrating plastic-derived syngas with conventional reductants.

Table 6. Comparative CAPEX and OPEX drivers for plastic-derived syngas versus conventional metallurgical reductants. Adapted from Lewis et al. (2022), Kulas et al. (2023), Tomić et al. (2024), and Kang et al. (2025).

Cost driver	Plastic-derived syngas	Coke / coal	Natural gas	Industrial implication
Feedstock preparation	High (sorting, drying, size control)	Low	Very low	Plastic requires pre-treatment infrastructure
Gas generation unit	High CAPEX (gasifier/pyrolysis reactor)	Notrequired	Notrequired	Additional core unitoperation
Gas cleanup system	Very high CAPEX (tar, HCl, H_2S, particulates, alkalis)	Low (dust removal)	Low (desulfurization only)	Dominant capital penalty
Gas compression/delivery	Medium–high	Low	Medium	Higher volumetric flow due to dilution
Refractory and materials	High wear rate	Established	Established	Shortened campaign life
Waste handling	High (scrubber effluents, spent sorbents)	Low	Low	Secondary waste streams
Energy efficiency	Low–moderate	High	High	Dilution reduces useful energy
Operational stability	Low	High	High	Frequent upsets increase OPEX
Maintenance frequency	High	Moderate	Low	Fouling and corrosion driven
Labor and monitoring	High (waste + gas compliance)	Moderate	Low	Regulatory burden
Availability (uptime)	<80–85% (typical trials)	>95%	>97%	Economics is dominated by downtime
OPEX predictability	Low	High	High	Variable feedstock drives cost volatility
Delivered reducing power cost	High	Low–moderate	Moderate	Poor competitiveness
Scale sensitivity	Strong (economy of scale needed)	Weak	Weak	Small plants penalized
Overall economic risk	High	Low	Low	Limits bankability

The economic penalty is structural rather than marginal. The dominant costs are gas cleaning, waste handling, and availability losses. Even under favorable assumptions, these penalties outweigh potential feedstock or circular-economy benefits relative to coke or natural gas. As a result, most industrial trials fail at the economic screening stage rather than at the thermodynamic feasibility stage.

Regulatory and Operational Risk

Regulatory exposure often becomes the deciding factor. Plastic-derived syngas systems can emit PCDD/F, volatile metals, and acid gases during upset or transient conditions. Even if average emissions are acceptable, peak events can trigger compliance issues (Lin et al., 2025a; Lin et al., 2025b).

Permitting becomes complex. Authorities treat plastic conversion as waste processing rather than a standard fuel supply. This increases monitoring requirements, reporting burdens, and public scrutiny (Ouedraogo et al., 2021; Stegmann et al., 2022).

Operationally, metallurgical plants are risk-averse. Introducing a new gas stream with variable composition and regulatory uncertainty threatens core production. When trials disrupt throughput or compliance, they are quickly terminated (Lewis et al., 2022; Wang et al., 2025).

Figure 10 illustrates how regulatory and operational risks interact and amplify during scale-up.

Figure 10: Interaction between regulatory, operational, and scale-up risks in plastic-derived syngas projects for metallurgical applications. Adapted from Tomić et al. (2024), Lewis et al. (2022), and Ciuffi et al. (2020).

Figure 10 explains why many trials stop after a pilot demonstration. Risk escalates faster than confidence.

The failure of industrial trials does not imply impossibility. It indicates that current approaches are insufficient. The next section poses a more constructive question: what would be required to make plastic-derived syngas viable in metallurgy?

What Would Be Required to Make It Viable

The failure of plastic-derived syngas in metallurgy does not imply that improvement is impossible. It implies that incremental adjustments are insufficient. Viability would require coordinated action across feedstock, gas conditioning, and process design. This section outlines what would be required, not merely what is desirable.

Feedstock-Level Solutions

The initial requirement is feedstock control, as metallurgy cannot handle undefined inputs. Mixed municipal plastic waste is inherently incompatible with consistent syngas production.

Dedicated plastic streams would be required. These streams must be low in chlorine and sulfur and free of problematic additives. Post-consumer packaging dominated by PE and PP is a minimum requirement. PVC, multilayer plastics, and halogenated polymers must be excluded upstream (Ma et al., 2024; Zhou et al., 2022).

Pre-treatment would be mandatory. Advanced sorting, dechlorination, and controlled blending would be required to limit variability. This shifts the challenge upstream but does not eliminate it. It also increases costs and narrows feedstock availability (Kulas et al., 2023; Gracida-Alvarez et al., 2023).

Table 7 summarizes the feedstock control requirements needed to approach metallurgical compatibility.

Table 7. Feedstock control and pre-treatment requirements for metallurgical-grade plastic-derived syngas. Adapted from Ma et al. (2024), Kulas et al. (2023), and Zhou et al. (2022).

Feedstock aspect	Requirement for metallurgical compatibility	Typical condition in mixed plastic waste	Implication for process viability
Polymer composition	Dominated by PE and PP (>80–90%)	Highly variable (PE, PP, PS, PVC, PET blends)	Unstable syngas chemistry
Chlorine content	<0.2 wt% (preferably<0.05 wt%)	0.5–5 wt% common (PVC, additives)	Severe corrosion and emissions
Sulfur content	As low as possible (<0.05 wt%)	Variable; often unknown	Increased H_2S and COS formation
Additives & fillers	Minimal (no halogenated FRs, low metals)	Widespread use of pigments, stabilizers	Trace metal and ash carryover
Moisture content	Controlled (<5 wt%)	Highly variable	Steam dilution and tar formation
Particlesize&form	Uniform; reactor-specific	Mixed shapes and sizes	Feeding and conversion instability
Contaminants (food, paper, dirt)	Negligible	Common in post-consumer waste	Ash, particulates, fouling
Pre-sorting requirement	Advanced optical + density separation	Basic mechanical sorting	Insufficient Cl and PVC removal
Pre-treatment steps	Dechlorination, washing, blending	Rarely applied	Upstream cost escalation
Feedstock blending strategy	Controlled, recipe-based	Ad hoc	No reproducibility
Supply consistency	Contracted, long-termstreams	Seasonal and market-dependent	Uptime and planning risk
Trace metals (Sb, Pb, Zn)	Defined upper limits	Often unmeasured	Accumulation in loops
Quality monitoring	Continuous or batch-verified	Sporadic sampling	Control system blind
Waste rejection rate	Acceptable losses	High rejection needed	Reduced yield
Feedstock cost	Stable, predictable	Volatile	Economic uncertainty

Achieving metallurgical compatibility requires feedstock conditions closer to those of specialty chemical recycling than to those of conventional waste processing. The need for stringent sorting, dechlorination, and blending shifts complexity upstream and significantly narrows the range of usable plastic streams. This explains why feedstock control, rather than thermochemistry, is the first hard barrier to viability.
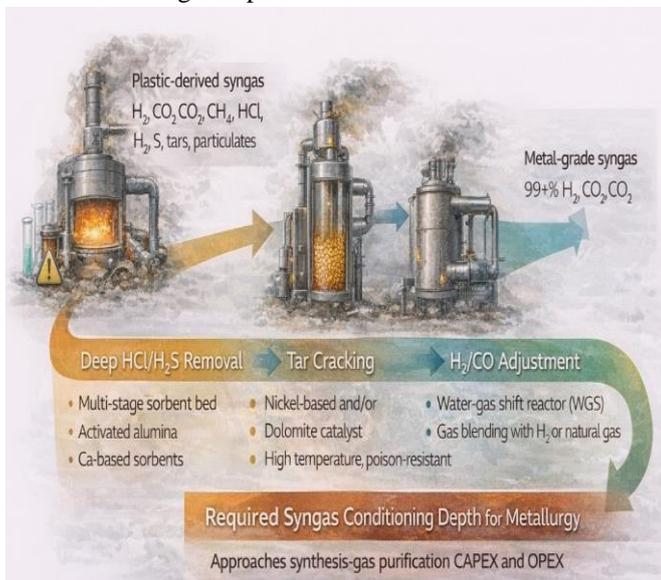
Syngas Conditioning Tailored to Metallurgy

Generic gas cleaning is insufficient. Metallurgy requires targeted syngas conditioning designed to achieve redox control and material compatibility.

Deep removal of HCl and H_2S would be essential. This would require multi-stage sorbent systems, hot-gas cleanup, and continuous monitoring. Single-step scrubbers are insufficient to meet metal-grade requirements (Rahim et al., 2023; Marcantonio et al., 2021).

Tar cracking must be robust under variable loads. Catalytic systems would need long lifetimes and resistance to poisoning. Most current solutions fail under real-world waste-derived syngas compositions (Madanikashani et al., 2022; Khalid et al., 2024).

Finally, H_2/CO adjustment would be necessary. This may involve water–gas shift, hydrogen blending, or co-feeding natural gas. At this point, plastic-derived syngas becomes a secondary contributor rather than a standalone reductant (Etminan et al., 2025; Lee et al., 2025).

Figure 11 illustrates the level of syngas conditioning required to meet metallurgical specifications.

Figure 11: Required syngas conditioning depth for metallurgical applications. Adapted from Ma et al. (2024), Kulas et al. (2023), Zhou et al. (2022), and Gupta et al. (2023).

Figure 11 makes clear that conditioning complexity approaches that of synthesis-gas preparation, with comparable CAPEX and OPEX.

Process Redesign

Even with controlled feedstock and conditioned syngas, existing furnaces are unsuitable. Process redesign is unavoidable.

Dedicated furnaces or reactors would be required. These units must be designed to handle diluted gases, higher flow rates, and variable calorific value. Retrofitting conventional furnaces is unlikely to succeed (Xu & Shi, 2022; Wang et al., 2025).

A more realistic role is auxiliary reduction or fuel substitution. Plastic-derived syngas may supplement hydrogen or natural gas, thereby reducing fossil intensity without requiring full redox control. This hybrid approach limits risk and improves controllability (Okolie et al., 2021; Tang et al., 2020).

Integration with **H_2 or natural gas** is therefore not optional. It is a prerequisite for stability. Fully plastic-based syngas routes remain unrealistic under current conditions (Lewis et al., 2022; Kang et al., 2025).

Figure 12 outlines a realistic integration pathway where plastic-derived syngas acts as a secondary, controlled input.
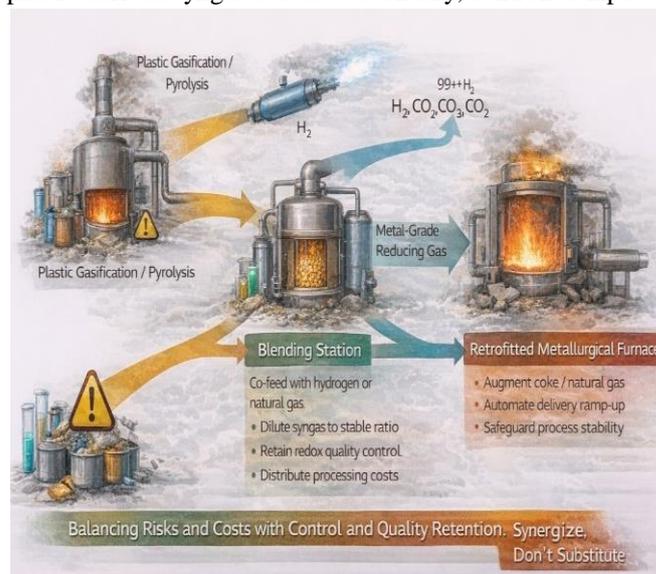
Figure 12: Realistic integration pathway for plastic-derived syngas as an auxiliary metallurgical reductant. Adapted from Tomić et al. (2024), Lewis et al. (2022), and Bachmann et al. (2023).

The figure underscores a key strategic conclusion of this review: plastic-derived syngas can be industrially viable only when used in synergy with established reductants and infrastructure. By shifting from a substitution paradigm to a blending-and-augmentation strategy, metallurgical plants can capture limited circularity benefits while preserving process robustness. This framing also clarifies why most successful concepts remain auxiliary and why expectations of direct, standalone metallurgical deployment are currently misplaced.

Meeting the requirements outlined above would significantly narrow the scope of application and increase costs. The final section, therefore, evaluates plastic-derived syngas from

environmental and cleaner production perspectives, asking whether such efforts deliver net sustainability benefits relative to alternatives.

Environmental and Cleaner Production Perspective

Plastic-derived syngas is often assumed to be a climate-friendly solution by default. This assumption is weak. Environmental performance depends on the carbon's origin, system boundaries, and what the syngas displaces. This section evaluates plastic-derived syngas through a cleaner production lens rather than through narrative alignment.

Carbon Accounting Pitfalls

Plastic waste is not biomass. Its carbon is fossil-derived. Using it as syngas does not achieve biogenic neutrality. At best, it merely reroutes fossil carbon, delaying release. At worst, it increases emissions through inefficient conversion and conditioning (Stegmann et al., 2022; Davidson et al., 2021).

Many assessments report avoided landfilling or incineration emissions while underreporting indirect emissions. Sorting, washing, dechlorination, gas cleanup, sorbent production, wastewater treatment, and residue disposal entail substantial upstream and downstream burdens (Gracida-Alvarez et al., 2023; Xayachak et al., 2023).

In metallurgical contexts, dilution further reduces carbon efficiency. More gas must be produced, purified, and transported to achieve the same reduction in emissions. This increases energy use and indirect CO_2 emissions per unit of metal produced.

Figure 13 illustrates typical carbon flow and hidden emission sources in plastic-derived syngas systems.

Figure 13: Carbon and energy flow in plastic-derived syngas systems, highlighting upstream and downstream burdens relevant to cleaner production assessment. Adapted from Davidson et al. (2021), Xayachak et al. (2023), Gracida-Alvarez et al. (2023), and Stegmann et al. (2022).

The figure shows that plastic-derived syngas does not inherently ensure a favorable carbon balance in metallurgical applications. When upstream and downstream burdens are fully accounted for, apparent furnace-level emission reductions may be offset or even reversed at the system level. This reinforces that cleaner production outcomes depend on comparative life-cycle performance rather than on isolated process substitutions, and explains why alternative pathways such as electrification, low-carbon hydrogen, or material recycling often deliver more robust environmental benefits.

Comparison with Alternatives

From a cleaner production perspective, plastic-derived syngas competes with several alternatives that are technically simpler and environmentally preferable.

Hydrogen

Low-carbon hydrogen offers higher reducing efficiency, no tar or chlorine, and simpler integration once infrastructure exists. Its main limitation is cost and availability, not operability (Lewis et al., 2022; Okolie et al., 2021).

Electrification

Electrified furnaces and plasma-assisted routes eliminate combustion-related emissions entirely. Although capital-intensive, they avoid the complexity of gas cleanup and the regulatory exposure associated with waste-derived fuels (Zhang et al., 2022; Wang et al., 2025).

Chemical Recycling to Monomers

For plastics, recovering monomers or polymer feedstocks often yields a higher circularity value than converting carbon to syngas and subsequently oxidizing it in metallurgy. This route preserves material value and reduces cumulative emissions when properly implemented (Thiounn & Smith, 2020; Roy et al., 2021).

Table 8 compares plastic-derived syngas with alternative decarbonization routes from a cleaner production perspective.

Table 8. Comparison of plastic-derived syngas, hydrogen, electrification, and chemical recycling routes under cleaner production criteria. Adapted from Lewis et al. (2022), Roy et al. (2021), Thiounn & Smith (2020), Davidson et al. (2021), and Stegmann et al. (2022).

Criterion	Plastic-derived syngas	Low-carbon hydrogen	Electrification	Chemical recycling to monomers
Carbon origin	Fossil (plastic-derived)	Depends on source (green/blue)	Depends on electricity mix	Fossil, but material-retained
Direct CO_2 emissions	Moderate–high	Low (green H_2)	Verylow	Low–moderate
Indirect emissions	High (sorting, cleanup, sorbents)	Moderate	Depends on grid	Moderate
Tar / chlorine issues	Severe	None	None	Controlled in process
Gas cleaning complexity	Very high	Low	None	Moderate
Process integration	Difficult	Moderate	High (retrofit-dependent)	Moderate
Operational stability	Low–moderate	High	High	High
Regulatory complexity	High (waste-derived fuel)	Moderate	Low–moderate	Moderate
Energy efficiency	Low–moderate	High	High	Moderate
Circularity value	Low (carbon destroyed)	Low	Low	High (material retained)
Scalability	Challenging	Improving	High	Improving
CAPEX intensity	High	High	High	High
OPEX predictability	Low	Moderate	High	Moderate
Technology maturity (TRL)	Pilot–early demo	Demo–commercial	Commercial	Demo–commercial
Cleaner production ranking	Low	High	Very high	High

Plastic-derived syngas consistently underperforms against cleaner production criteria. Its main disadvantage is not a single parameter but rather the accumulation of indirect emissions, operational instability, and regulatory burden. In contrast, electrification and low-carbon hydrogen directly address emissions without introducing the complexity of waste-derived fuels. Chemical recycling preserves material value and often delivers superior circularity outcomes.

Critical Assessment and Research Gaps

The analysis presented in this review leads to a clear conclusion: the gap between academic promise and industrial reality for plastic-derived syngas in metallurgy is not marginal. It is structural. This conclusion is consistent across techno-economic evaluations, pilot-scale experiences, and industrial benchmarking reported in the literature (Tomić et al., 2024; Lewis et al., 2022).

Lack of Dedicated Kinetic Data

Thermodynamic feasibility is repeatedly demonstrated, whereas kinetic viability is not. Most studies rely on equilibrium calculations or short-duration laboratory tests that do not reflect industrial gas–solid or gas–liquid reduction conditions. Dedicated kinetic data for oxide reduction with diluted, transient, contaminant-bearing syngas are largely absent.

Reaction rates under realistic partial pressures of CO and H_2, in the presence of CO_2, H_2O, and trace contaminants, remain poorly quantified. Without these data, residence-time requirements cannot be determined, and reactor sizing remains speculative. This gap has been explicitly highlighted in multiscale modeling and scale-up analyses, in which kinetic and transport effects dominate process performance (Madanikashani et al., 2022; Xu & Shi, 2022).

Limited Integrated Modeling

Existing models often isolate different subsystems: gasification is modeled separately from gas cleanup, which is also decoupled from delivery. Reduction is considered a distinct, idealized step. Very few studies integrate variables such as feedstock variability, gas composition, cleanup efficiency, delivery losses, and reduction kinetics into a unified framework.

This fragmentation leads to overly optimistic conclusions that do not hold up at scale. Integrated, dynamic models that capture transient behavior, contaminant accumulation, and control limitations remain rare. Consequently, techno-economic assessments systematically underestimate operational risk and overestimate robustness (Madanikashani et al., 2022; Tomić et al., 2024).

Absence of Real Metallurgical Pilot Campaigns

Most documented demonstrations conclude with energy production, laboratory reactors, or brief pilot runs. Genuine metallurgical pilots are absent. By "real," this review refers to campaigns that:

- operate continuously for hundreds to thousands of hours,
- inject syngas into metallurgical reactors or residue-treatment units,

- expose refractories, burners, and off-gas systems to real contaminant loads,
- report availability, maintenance, and emissions under upset conditions.

The absence of such campaigns explains why claims of metallurgical applicability remain unvalidated despite years of research. Energy-focused pilots do not provide the data needed to assess metallurgical viability (Nielson et al., 2021; Lewis et al., 2022).

Confusion between Energy Viability and Metallurgical Viability

A common misconception is that success in energy applications automatically means success in metallurgy. This is not accurate, as metallurgy imposes stricter requirements on gas quality, redox control, kinetics, and material compatibility than power generation or synthesis processes.

The literature often conflates "usable fuel gas" with "metallurgical-grade reducing gas." This conceptual confusion has been explicitly identified in studies of metallurgical integration and cleaner production assessments, where energy-oriented metrics fail to predict metallurgical performance (Nielson et al., 2021; Stegmann et al., 2022).

Lack of Clear Decision Criteria

Finally, most studies fail to define decision thresholds. Viability is discussed qualitatively without specifying:

- Minimum acceptable syngas quality,
- Maximum tolerable contaminant levels,
- Minimum availability targets,
- Economic cutoffs relative to coke, natural gas, hydrogen, or electrification.

Without explicit criteria, negative results cannot be conclusively determined, and positive claims cannot be falsified. This lack of decision logic perpetuates ambiguity and delays rational investment and policy decisions (Tomić et al., 2024; Lewis et al., 2022).

Synthesis

The research gaps identified here explain why plastic-derived syngas remains at a low TRL for metallurgical use. Progress will not come from more equilibrium diagrams or incremental reactor tweaks. It will come only from targeted kinetic studies, fully integrated modeling, real-world metallurgical pilots, and explicit go/no-go criteria.

Recognizing these gaps allows the discussion to proceed constructively. The final section outlines future perspectives, focusing on where research effort is justified, where it is not, and how to avoid repeating the same dead ends.

Future Perspectives

Future work on plastic-derived syngas should move beyond broad claims of metallurgical substitution and focus on narrow, well-defined roles where technical risk is manageable and value creation is defensible. The perspectives below reflect realistic directions rather than general optimism.

Syngas as a Hydrogen Source, Not a Direct Reductant

The most credible pathway is to treat plastic-derived syngas as an intermediate for hydrogen production rather than as a metallurgical reductant. After deep cleaning and reforming, hydrogen can be separated and used where H_2 already aligns with process logic and control strategies.

This reframing shifts the focus. Metallurgy interacts with hydrogen quality, not with variability in waste-derived gas. The cost and energy penalty remain significant, but operability and materials compatibility improve markedly. In this configuration, syngas serves as a feedstock for a hydrogen system rather than as a furnace input.

Hybrid Systems (Syngas + H_2)

Fully plastic-based syngas routes are unlikely to be feasible. Hybrid approaches are a more practical solution. These systems use syngas from plastics to supply part of the energy or carbon, while hydrogen or natural gas is used to ensure redox stability and control the process.

Such blending strategies reduce exposure to variability and contaminants. They also enable gradual decarbonization without requiring the redesign of entire furnaces. Importantly, hybrids enable graceful failure: if syngas quality drops, the system can revert to the primary reductant without shutdown.

Integrated Industrial Clusters

Isolated plants magnify risk. Industrial clusters reduce it. Co-location of waste sorting, gasification, hydrogen production, metallurgy, and off-gas treatment enables shared infrastructure, centralized cleanup, and improved integration of heat and materials.

Clusters also enable specialization. Plastic-derived syngas can be produced where waste logistics are feasible and consumed where tolerance is higher. This spatial decoupling is often overlooked in single-plant concepts but is essential for any realistic deployment.

Digital Twins for Redox Control

One consistent weakness across studies is the lack of real-time redox control. Future systems must rely on digital twins that integrate feedstock variability, gas composition, cleanup efficiency, delivery losses, and reactor response.

Digital twins are not optional optimization tools. They are prerequisites for stability. Without predictive control and fast feedback, variable syngas streams cannot be safely or efficiently integrated into metallurgical environments.

Intermediate-Scale Demonstrations

The next step is not full-scale deployment. It is an intermediate-scale demonstration with clear success criteria. These demonstrations must:

- Operate continuously for extended periods,
- Use real plastic-derived syngas with documented variability,
- Inject into metallurgical or residue-treatment units,
- Report availability, emissions, maintenance, and economics transparently.

Brief pilots and energy-only demonstrations are no longer adequate. Without intermediate-scale metallurgical evidence, additional claims will have limited value.

Perspective Summary

Future progress depends on redefining expectations. Plastic-derived syngas is unlikely to become a universal metallurgical reductant. It may, however, play a supporting role in hydrogen supply, hybrid systems, and clustered industrial configurations—provided that control, cleanup, and scale are explicitly addressed.

These perspectives frame plastic-derived syngas as a conditional enabling technology rather than a cornerstone solution. The conclusions synthesize the review's findings and provide a clear answer to the central question of industrial viability.

Conclusions

This critical review set out to answer a practical question: why has plastic-derived syngas not become an industrial metallurgical reductant despite decades of research and repeated claims of feasibility? The answer is now clear.

The main barrier to the metallurgical use of plastic-derived syngas is not chemical. Thermodynamic feasibility is well established, and reduction by CO and H_2 is not in dispute. The real barriers are gas quality, process integration, and operational robustness.

Plastic-derived syngas is inherently variable. Feedstock heterogeneity, contaminant formation, and transient operating conditions prevent the delivery of a stable, metal-grade reducing gas. Without stringent feedstock control and deep gas conditioning, dilution, tar, chlorine, sulfur, and particulates dominate process behavior rather than reduction chemistry.

Integration failures further limit viability. Existing metallurgical furnaces are not designed to handle diluted and contaminated gas streams. Retrofitting increases complexity, downtime, and regulatory exposure. As a result, most industrial trials stall at pilot scale, not because reduction is impossible, but because reliability and availability cannot be sustained.

From an environmental perspective, plastic-derived syngas does not automatically qualify as a cleaner production route. The carbon in plastics is fossil in origin, and indirect emissions from sorting, cleaning, and conditioning are substantial. When evaluated consistently against hydrogen,

electrification, or chemical recycling, syngas from plastic recycling is rarely the preferred option.

Nevertheless, this review does not argue for abandonment. Plastic-derived syngas may play a limited, conditional roleas:

- An auxiliary reductant or fuel in secondary metallurgy and residue treatment,
- An intermediate for hydrogen production,
- A component of hybrid systems combined with hydrogen or natural gas,
- Part of integrated industrial clusters with shared infrastructure and control.

However, without dedicated feedstock control, deep gas conditioning, and purpose-built process design, syngas from plastic recycling will remain a marginal auxiliary rather than a primary metallurgical reductant.

The implications for research and policy are clear. Progress will require fewer conceptual studies and more integrated, long-duration metallurgical demonstrations with explicit go/no-go criteria. Until such evidence exists, claims of broad industrial viability should be treated with caution.

In this sense, plastic-derived syngas is not a failed technology. It is a **misapplied one**.

Declarations

Conflicts of Interest

The author declares that there are no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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