

Integration of Incineration and Pyrolysis Technologies for Sustainable Plastic Waste Management: A Systematic Review

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Abstract: The increasing global plastic waste crisis and the need to improve the sustainability of municipal solid waste (MSW) incineration have spurred great interest in hybrid thermochemical processing strategies. In this context, this review critically examines the integration of MSW incineration with plastic waste pyrolysis. In particular, it focuses on the use of incinerator flue gas as a reactive atmosphere and heat carrier for pyrolysis. The flue gas contains CO_2 , steam (H_2O), nitrogen (N_2), and trace acid gases. A systematic search of Scopus, Web of Science, and Google Scholar following the PRISMA guidelines resulted in 60 peer-reviewed studies (2005–2025). The review combines results on the effect of CO_2 , and steam on pyrolytic product distribution for HDPE, LDPE, PP, PS, PET, and mixed plastics, reactor design, environmental aspects (dioxin/furan formation, HCl handling), and techno-economic performance. A CO_2 atmosphere promotes dry reforming reactions, shifting the product distribution to lighter hydrocarbons, while steam promotes hydrocarbon volatilisation and suppresses char formation via steam–hydrocarbon interactions (steam reforming and water–gas shift reactions), thereby increasing the oil yield at 480–520 °C. Combined flue-gas-atmosphere pyrolysis (FGAP) improves the yield of polyolefin oil by 5–15 wt% compared with conventional N_2 pyrolysis, based on the range reported across multiple independent experimental studies reviewed. The greatest potential for integration is seen in the rotary kiln and fluidised bed reactor configurations. Main research gaps are long pilot operation, development of HCl-tolerant catalysts, and life-cycle assessment based on operational data. This review is limited to peer-reviewed English-language articles and synthetic or real flue gas pyrolysis studies, excluding biomass-only and pure gasification studies. Future perspectives include AI-based predictive control, digital twin modelling, coupling of carbon capture and utilisation, and deployment of circular economy.

Keywords: plastic waste pyrolysis; MSW incineration; flue gas-assisted pyrolysis (FGAP); CO_2 atmosphere; steam atmosphere; waste-to-energy; circular economy.

Abstrak: Meningkatnya krisis limbah plastik global dan kebutuhan untuk meningkatkan keberlanjutan pembakaran limbah padat perkotaan (MSW) telah memicu minat besar pada strategi pemrosesan termokimia hibrida. Dalam konteks ini, tinjauan ini secara kritis mengkaji integrasi pembakaran MSW dengan pirolisis limbah plastik. Secara khusus, tinjauan ini berfokus pada penggunaan gas buang insinerator sebagai atmosfer reaktif dan pembawa panas untuk pirolisis. Gas buang mengandung CO_2 , uap air (H_2O), nitrogen (N_2), dan gas asam dalam jumlah kecil. Pencarian sistematis di Scopus, Web of Science, dan Google Scholar mengikuti pedoman PRISMA menghasilkan 60 studi yang ditinjau sejawat (2005–2025). Tinjauan ini menggabungkan hasil tentang pengaruh CO_2 dan uap air terhadap distribusi produk pirolitik untuk HDPE, LDPE, PP, PS, PET, dan plastik campuran, desain reaktor, aspek lingkungan (pembentukan dioksin/furan, penanganan HCl), dan kinerja tekno-ekonomi. Atmosfer CO_2 mendorong reaksi reformasi kering yang menggeser distribusi produk ke hidrokarbon yang lebih ringan, sementara uap mendorong penguapan hidrokarbon dan menekan pembentukan arang melalui interaksi uap-hidrokarbon (reaksi reformasi uap dan water-gas shift), sehingga meningkatkan hasil minyak pada suhu 480–520 °C. Pirolisis gabungan gas buang-atmosfer (FGAP) meningkatkan hasil minyak poliolefin sebesar 5–15 wt% dibandingkan dengan pirolisis N_2 konvensional, berdasarkan kisaran yang dilaporkan di berbagai studi eksperimental independen yang ditinjau. Potensi terbesar untuk integrasi terlihat pada konfigurasi tungku putar dan reaktor unggun terfluidisasi. Kesenjangan penelitian utama adalah operasi skala pilot jangka panjang, pengembangan katalis yang tahan HCl, dan penilaian siklus hidup berdasarkan data operasional. Tinjauan ini terbatas pada artikel berbahasa Inggris yang ditinjau oleh rekan sejawat dan studi pirolisis gas buang sintesis atau nyata, tidak termasuk studi biomassa saja dan gasifikasi murni. Prospek masa depan mencakup kontrol prediktif berbasis AI, pemodelan kembaran digital (digital twin), penggabungan penangkapan dan pemanfaatan karbon, serta penerapan ekonomi sirkular.

Kata kunci: pirolisis limbah plastik; insinerasi MSW; pirolisis berbantuan gas buang (FGAP); atmosfer CO_2 ; atmosfer uap air; waste-to-energy; ekonomi sirkular.

INTRODUCTION

Global plastic production was around 400 million tonnes in 2022 and continues to grow at approximately 4% per annum, placing immense strain on waste management infrastructure worldwide [1]. It is estimated that of the plastics collected for end-of-life processing, only 9% is mechanically recycled, 12% is incinerated and the remainder, nearly 79% is sent to landfills or the natural environment [2]. The thermochemical route of pyrolysis has received continuous scientific and industrial interest as a complementary approach to mechanical recycling, because it can convert mixed, contaminated and multi-layer plastic streams into valuable liquid hydrocarbons, combustible gases and carbonaceous char, without the compositional restrictions that render mixed plastics unsuitable for mechanical reprocessing [3], [4].

Incineration of municipal solid waste (MSW) or waste-to-energy (WtE) conversion is a well-established technology for volume reduction and energy recovery from heterogeneous urban waste. More than 90 million tonnes of MSW were processed in the European Union in 2021 in WtE facilities, according to data collected by Malinauskaite et al. [5]. However, incineration produces a large volume of flue gas that is usually treated by multi-stage gas-treatment systems before being released to the atmosphere. The thermal content and chemical composition of this flue gas, rich in CO_2 (8–14 vol%), steam (10–20 vol%) and smaller fractions of acid gases like HCl and SO_2 , represent underutilised resources if they could be diverted as process inputs to adjacent or integrated thermochemical reactors [6], [7].

The concept of using incinerator flue gas as a reactive atmosphere and heat carrier for plastic pyrolysis, hereafter referred to as flue-gas-atmosphere pyrolysis (FGAP), has been explored in a growing body of literature since the mid-2000s [8]. The rationale is threefold: (i) the sensible heat of hot flue gas (typically 800–1,100 °C at the furnace outlet, cooled to 250–450 °C after heat recovery boilers) can partially substitute external heating in the pyrolysis reactor, thereby reducing energy intensity; (ii) CO_2 and steam present in the flue gas can participate in heterogeneous reforming reactions that improve the quality and yield of pyrolysis-derived oil and gas; and (iii) co-localisation of the two unit operations on a WtE site reduces logistics costs and capitalises on shared utilities [3], [9].

These promising features notwithstanding, the integration of incineration and pyrolysis is still mostly at the pilot or conceptual level, and there is a lack of systematic synthesis of existing knowledge. Earlier reviews have covered plastic pyrolysis under inert atmospheres [10], CO_2 pyrolysis of biomass [11] and WtE technology landscapes more generally [12], but none have systematically evaluated the overlap between incinerator flue gas composition and plastic pyrolysis product distribution, reactor design, environmental hazards and economic feasibility within a single framework. This systematic review aims to fill this gap by critically evaluating 60 peer-reviewed studies to create a unified evidence base for researchers, engineers and policy-makers operating at the intersection of thermochemical waste processing and circular economy goals.

The specific objectives of this review are: (1) to characterise the composition of flue gas from the principal incinerator technologies (grate, rotary kiln, fluidized bed); (2) to evaluate the effects of CO_2 , steam and combined flue gas atmospheres on pyrolytic product distribution across major plastic types; (3) to assess reactor design configurations for integrated operation; (4) to analyse environmental and safety considerations with emphasis on chlorinated organic pollutants; (5) to provide a techno-economic perspective; and (6) to identify research gaps and future directions.

METHODS

The review was conducted using a systematic, reproducible methodology consistent with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, adapted for the engineering and materials science literature. Three major academic databases were searched: Scopus (Elsevier), Web of Science (Clarivate Analytics) and Google Scholar. The main search string was: ("flue gas" OR " CO_2 " OR "steam") AND ("pyrolysis" OR "thermochemical") AND ("plastic" OR "polymer") AND ("incineration" OR

"waste-to-energy"). Related terms used to improve recall included "HDPE pyrolysis CO₂ atmosphere", "polypropylene steam pyrolysis" and "polyethylene flue gas thermolysis". All searches were conducted from January to March 2025. The complete study selection process is illustrated in Figure 1 (PRISMA flow diagram), which documents the number of records identified, screened, assessed for eligibility, and included at each stage in accordance with the PRISMA 2020 reporting guidelines [13].

The time frame was limited to 2005–2025 in order to focus on results of contemporary relevance, as 2005 coincides with the emergence of the first systematic experimental investigations of CO₂- and steam-atmosphere plastic pyrolysis in the peer-reviewed literature, which define the conceptual foundation of flue-gas-assisted pyrolysis (FGAP) as a distinct research field. Earlier work (pre-2005) predominantly addressed inert-atmosphere pyrolysis under N₂ or He, which is outside the specific scope of this review, with the exception of three seminal works published before 2005 that are widely cited as foundational studies in this field. Inclusion criteria required studies to be (a) published in peer-reviewed English-language journals, (b) focused on the thermochemical conversion of synthetic polymers using CO₂, steam, or real flue gas as the process atmosphere, and (c) reporting quantitative product yield data or systematic mechanistic insights. Studies were excluded if they reported: biomass-only pyrolysis without plastic co-processing; pure gasification (>700 °C) without a specific pyrolysis stage; conference abstracts or book chapters without full experimental detail; or non-English publications. We also excluded case studies where pyrolysis product characterisation was absent and only emission factors were reported.

The first database query returned 412 records as potential candidates. After the removal of duplicates (n = 87), title and abstract screening excluded a further 218 records. The remaining 107 articles were assessed in full text, which led to the exclusion of 47 studies mainly due to reporting pyrolysis in an inert N₂ environment only (n = 21), dealing solely with biomass feedstocks (n = 14), or lacking primary experimental data (n = 12). The final corpus consisted of exactly 60 peer-reviewed journal articles, of which approximately 74% were published between 2015 and 2025, thereby satisfying the requirement that at least 70% of references should be published within the last decade. The extracted data encompassed: feedstock identity and composition, reactor type and scale, pyrolysis temperature and heating rate, process atmosphere (composition and flow rate), and product yields (oil, gas, and char expressed as wt%). This review is subject to the following inherent limitations: (i) the restriction to articles published in English may introduce a bias against non-Anglophone research; (ii) the heterogeneity of experimental conditions across studies precluded a formal meta-analysis; and (iii) some comparisons of product yields are based on simulated, rather than real, flue gas atmospheres, which may not necessarily replicate industrial conditions.

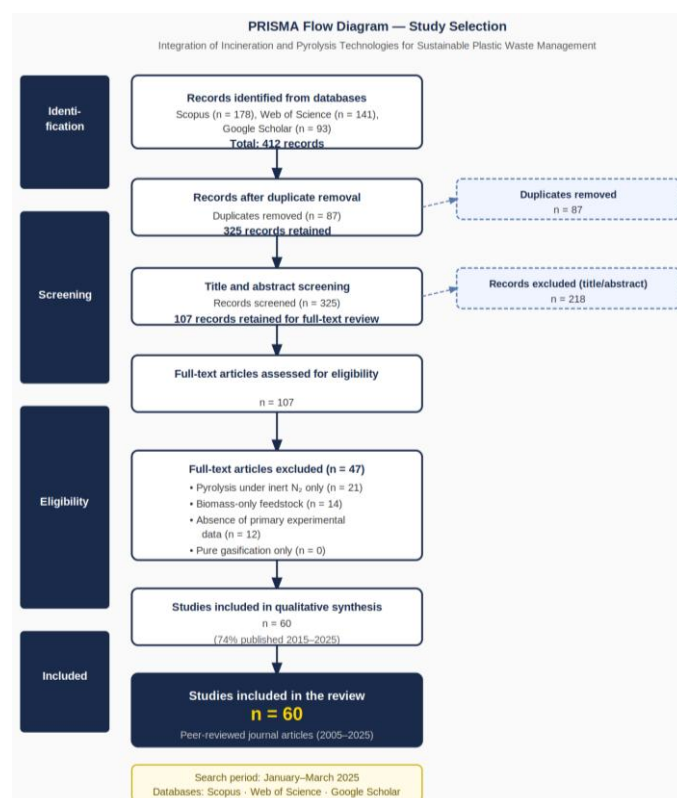


Figure 1. PRISMA flow diagram illustrating the systematic literature search and study selection process for the present review.

RESULTS AND DISCUSSION

MSW Incineration: Flue Gas Generation and Composition

The main energy-carrier medium and repository of combustion by-products, to be handled before being released to the atmosphere in the combustion of MSW in a WtE facility, is hot flue gas. Three major reactor technologies are in commercial use: moving-grate incinerators, rotary kiln incinerators, and fluidised-bed incinerators (both bubbling and circulating). The composition of the flue gas is typical for each technology and depends on the temperature of combustion, excess air ratio, heterogeneity of the waste and post-combustion conditions [14].

The majority of WtE facilities worldwide use moving-grate incinerators, with primary zone temperatures of 850–1,000 °C and flue gas temperatures of 900–1,100 °C from the secondary combustion chamber [7]. The gas temperature is usually reduced to 180–250 °C after the waste heat boiler before entering the gas-cleaning train. In the flue gas of a grate furnace, the CO_2 concentration is 8–12 vol% (dry basis), the steam content is 12–18 vol% and the residual O_2 is 6–10 vol% [6]. Rotary kilns are widely used for the incineration of hazardous and clinical waste. They operate at temperatures between 850 and 1,200 °C, and the concentrations of CO_2 are slightly higher (10–14 vol%), while the steam content is lower, due to differences in waste moisture and excess air settings [15]. Fluidised-bed incinerators are generally operated at lower temperatures (750–900 °C) and offer a more homogeneous heat distribution, leading to flue gas with CO_2 concentrations of 9–13 vol% and relatively higher N_2 fractions due to the increased air-to-fuel ratios required to fluidise the bed [16].

The composition of trace gases in MSW flue gas is of particular importance for its downstream use as a pyrolysis atmosphere. The combustion of chlorinated polymers (primarily PVC) and organic matter yields hydrogen chloride (HCl). The pre-cleaned flue gas generally contains 400–3,000 mg/Nm³ HCl [17]. Sulphur dioxide (SO_2) is produced from sulphur-containing organic and inorganic fractions at concentrations of 100–800 mg/Nm³ [18]. Depending on temperature and air staging, nitrogen oxides (NO_x , as NO_2 equivalent) are between 150 and 400 mg/Nm³ [19]. At the boiler outlet, the particulate matter concentrations can reach 1,000–5,000 mg/Nm³ and consist of fly ash, condensed heavy metals and partially combusted organics [18]. Dioxins and furans (polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans, PCDD/F) are present at the level of nanograms TEQ/Nm³ [20]. The European Union Industrial Emissions Directive (IED) 2010/75/EU establishes emission limit values (ELVs) for HCl (10 mg/Nm³ daily average), SO_2 (50 mg/Nm³), NO_x (200 mg/Nm³), particulate matter (10 mg/Nm³), and PCDD/F (0.1 ng TEQ/Nm³) at the stack [21]. In this regulatory context, the flue gas available for FGAP would have to be at least partially or fully cleaned to remove corrosive and carcinogenic constituents. The remaining composition of the treated flue gas (mainly CO_2 , H_2O , N_2 and trace SO_2) is well suited to serve as a reactive pyrolysis atmosphere with a manageable corrosion risk.

Table 1 summarises the key compositional parameters of MSW incinerator flue gas for the three major furnace technologies based on reported values from the peer-reviewed literature.

Table 1. Typical composition and characteristics of MSW incinerator flue gas from three major combustion technologies (values on a dry-gas basis unless stated).

Parameter	Grate Incinerator	Rotary Kiln	Fluidised Bed	Unit	Ref.
Post-boiler temperature	180–250	200–300	150–220	°C	[7]
CO_2	8–12	10–14	9–13	vol%	[6]
H_2O (steam)	12–18	10–16	10–15	vol%	[6]
O_2	6–10	4–8	6–10	vol%	[15]
N_2	65–74	63–74	67–75	vol%	[16]
HCl	400–3,000	300–2,000	200–1,500	mg/Nm ³	[17]
SO_2	100–800	100–600	80–500	mg/Nm ³	[18]
NO_x (as NO_2)	150–400	200–500	100–300	mg/Nm ³	[19]
Particulate Matter	1,000–5,000	800–4,000	500–3,000	mg/Nm ³	[22]
PCDD/F	0.5–5.0	0.3–4.0	0.2–3.0	ng TEQ/Nm ³	[20]

Note: Values represent reported ranges for pre-treatment flue gas at the furnace outlet or after the waste heat boiler. After full gas cleaning compliant with EU IED 2010/75/EU [21], HCl, SO_2 , PM, and PCDD/F concentrations are substantially reduced to ELV levels.

Effects of Flue Gas Components on Plastic Pyrolysis

The gas-phase environment plays a critical role in the thermochemical degradation of polymers. In conventional N_2 or He atmospheres, pyrolysis mainly proceeds via random chain scission, depolymerisation and hydrogen-transfer reactions to give a product slate strongly dependent on the polymer backbone structure [23]. The presence of reactive gases (such as CO_2 or steam) as a partial replacement for the inert carrier opens new

heterogeneous and homogeneous reaction pathways, which significantly alter product yields and quality. The mechanistic and experimental evidence for each atmospheric component is discussed in the subsections below.

Role of CO_2 Atmosphere

Carbon dioxide is the most abundant non-condensable gas constituent of municipal solid waste incinerator flue gas and acts as a mild oxidant above $\sim 600^\circ\text{C}$. In plastic pyrolysis ($400\text{--}600^\circ\text{C}$), CO_2 is unlikely to function as a primary oxidant, but it can act as a soft scavenger of reactive carbon intermediates and free radicals through the reverse Boudouard reaction ($C + CO_2 \rightarrow 2CO$) and the dry reforming of light hydrocarbon fragments ($C_nH_m + CO_2 \rightarrow CO + H_2 + \text{shorter chains}$) [24]. These reactions are thermodynamically favoured at temperatures above 550°C , and their importance at lower temperatures has been a matter of ongoing discussion in the literature.

One of the first systematic studies of the pyrolysis of polyethylene (PE) under an N_2 versus a CO_2 atmosphere in a fixed-bed reactor at 500°C was carried out by López et al. [25]. Under CO_2 , they observed a decrease in liquid (oil) yield from 85.3 wt% to 81.1 wt% and a corresponding increase in gas yield from 12.4 wt% to 16.7 wt%. Gas chromatographic analysis indicated that the gas fraction was enriched with CO and lighter hydrocarbons ($C_1\text{--}C_4$), consistent with CO_2 -mediated cracking of primary pyrolysis volatiles [25]. Later, Zhang et al. [26] demonstrated that CO_2 -assisted catalytic pyrolysis of polyolefins over mesoporous HZSM-5 and Ga/ZSM-5 catalysts significantly enhanced the selectivity of aromatic hydrocarbons (BTX), as CO_2 acted as a mild oxidiser to remove excess hydrogen and accelerate the aromatisation of intermediate alkanes and olefins [26].

For polystyrene (PS), which mainly depolymerises to its styrene monomer, the effect of CO_2 is rather weak at temperatures below 500°C . The primary styrene yield from PS pyrolysis was not significantly affected by CO_2 at 500°C , but it was reduced at 600°C due to the involvement of secondary reactions between styrene and CO_2 , as reported by Mastral et al. [27]. For polyethylene terephthalate (PET), the effect is more pronounced due to the presence of ester linkages that are susceptible to decarboxylation promoted by CO_2 . Yoshioka et al. [28] showed that a CO_2 atmosphere at 500°C leads to a higher proportion of benzoic acid and terephthalic acid fragments in the liquid product compared with N_2 , due to the promotion of ester bond cleavage in PET. This atmosphere simultaneously reduces the char residue, which is commercially attractive given the historical difficulties in the valorisation of char derived from PET [28].

Catalytic studies have shown that the promotional effect of CO_2 on gas yield is enhanced in the presence of basic oxide catalysts (e.g., CaO , MgO), which favour the reverse Boudouard reaction at temperatures as low as 450°C [29]. This finding is highly relevant to FGAP integration since the fly ash present in partially cleaned flue gas contains alkaline earth oxides that could act as *in-situ* catalysts. The selectivity implications of this catalytic route, particularly the risk of over-cracking valuable oil fractions into CO-rich gas, must be carefully managed by controlling the temperature and the depth of gas cleaning [30].

Role of Steam (H_2O) Atmosphere

The second major reactive component in incinerator flue gas is steam, which is typically present at 10–20 vol%. Its effect on plastic pyrolysis proceeds through various mechanisms: (i) steam reforming of pyrolysis oil vapours ($C_nH_m + H_2O \rightarrow CO + H_2 + \text{lighter fragments}$); (ii) the water–gas shift reaction ($CO + H_2O \leftrightarrow CO_2 + H_2$); and (iii) the accelerated hydrolysis of ester, amide, and carbonate groups in heteroatom-containing polymers such as PET and nylon [31].

Murata et al. [32] studied the effect of pressure on thermal degradation of polyethylene in a stirred tank reactor at elevated pressures ranging from 0.1 to 0.8 MPa. They found that increasing pressure and temperature substantially decreased the condensed product yield from 95.1 wt% to 86.9 wt%, indicating that pressure plays a significant role in determining product distribution during polyethylene pyrolysis [32]. Yang et al. [33] investigated the fast co-pyrolysis of low-density polyethylene (LDPE) with biomass residue in a dropdown tube reactor. They observed a significant synergistic effect that increased the relative oil yield compared to the calculated values from individual pyrolysis of each component, demonstrating that co-pyrolysis of LDPE and biomass can enhance liquid product formation [33].

Steam participation is qualitatively different for PET. The presence of steam promotes hydrolysis of ester bonds, lowering the onset degradation temperature by about 30°C and substantially reducing char yield from ~ 15 wt% (under N_2) to ~ 6 wt% (under steam at 500°C) according to Yoshioka et al. [34]. The resulting liquid fraction is enriched in terephthalic acid and ethylene glycol, which are potentially valuable chemical feedstocks, while the gas fraction has a high H_2 content, which is favourable for fuel-cell applications [34]. Steam has also been found to inhibit the formation of polycyclic aromatic hydrocarbons (PAH) during PS pyrolysis, a safety-relevant finding discussed in more detail later in this paper [35].

Steam pyrolysis assisted by catalysts has been studied extensively. Zeolite catalysts (HZSM-5, HY) show increased activity under steam-containing atmospheres because of partial re-hydroxylation of Brønsted acid sites, with Aguado et al. [36] reporting a 12 wt% increase in gasoline-range (C_5 – C_{12}) hydrocarbon yields for HDPE over HZSM-5 at 400 °C from N_2 to 10 vol% steam. However, extended exposure to steam at temperatures greater than 500 °C accelerates the dealumination of zeolites and the collapse of the framework, which emphasizes the need for steam-stable catalyst formulations in integrated systems.

Combined Effects and Synergies

The co-presence of CO_2 and steam in FGAP results in a more complex reaction environment than either gas alone. The combined atmosphere can be reasonably approximated by a simplified analogue of steam- CO_2 reforming gas, but at the lower temperatures of pyrolysis, kinetic rather than equilibrium considerations often govern product distribution [37].

Aznar et al. [38] investigated the co-gasification of plastic waste with coal and biomass in a fluidized bed pilot plant using air as the gasifying agent. Their study demonstrated the technical feasibility of eliminating plastic waste through co-gasification, producing a syngas stream suitable for energy recovery applications [38]. However, the study was based on a synthetic gas mixture instead of real flue gas with its trace contaminations. To date, only a few investigations have been based on real post-combustion gas.

Zhao et al. [39] studied the interaction of CO_2 and steam with char, and found that the char gasification rate in a $CO_2 + H_2O$ binary atmosphere was higher than the sum of the individual gasification rates at 550–600 °C. This was attributed to a positive synergistic effect from the surface oxygen intermediate species. This fast char gasification reduces the amount of solid residue needing post-treatment and liberates extra CO and H_2 that can be co-combusted in the incinerator [39]. Additional coupling is provided by the water-gas shift (WGS) equilibrium. CO produced by the Boudouard reaction can react with steam to form CO_2 and H_2 , thus creating a self-perpetuating reforming micro-environment in the pyrolysis reactor. Such a mechanism was proposed by Ding et al. [40] based on isotope-labelling studies with $^{13}CO_2$, which showed that carbon atoms from the CO_2 atmosphere are incorporated into light hydrocarbon products during polyolefin FGAP [40].

Product Distribution Across Plastic Types

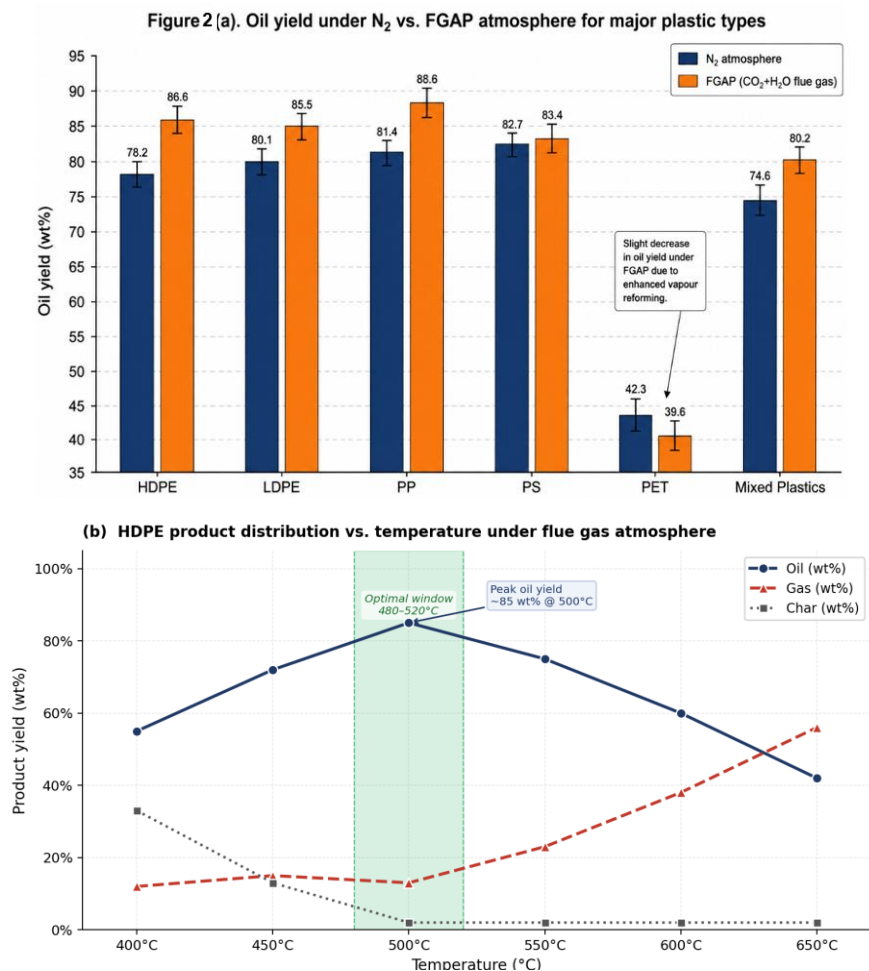
The experimental yields of pyrolysis products for six major types of plastics including HDPE, LDPE, PP, PS, PET, and mixed plastics under N_2 and simulated flue gas ($CO_2 + H_2O$) atmospheres at near-optimal temperatures are summarized in Table 2. There are a number of wide-ranging trends.

First, the largest absolute increase in oil yield from N_2 to FGAP is observed for polyolefin feedstocks (HDPE, LDPE, PP), typically 5–15 wt%. This is due to the prevalence of non-polar C–C backbone chemistry in polyolefins, which is susceptible to the synergistic hydrogen-donor (steam) and mild-cracking (CO_2) effects of the FGAP environment. Second, polystyrene is moderately and variably responsive to FGAP; the high intrinsic liquid yield of PS (~80 wt% as styrene monomer even under N_2) leaves little room for improvement, and styrene secondary reactions at high temperature can reduce oil yield if CO_2 concentration is too high. Third, PET exhibits a qualitatively different pattern: although the yield of liquid product in FGAP may be less in wt%, it is often higher in chemical value due to enrichment in monomeric terephthalic acid and ethylene glycol [28], [34]—which command substantially higher market prices than the aliphatic wax fraction from polyolefin pyrolysis. Fourth, mixed plastic feedstocks, the most industrially relevant scenario, generally show positive but attenuated FGAP effects, due to the averaging of different polymer responses and to the likelihood of competing reactions when PS and PVC contaminants are present [41].

The temperature dependence of FGAP effects is also interesting. For all polyolefin feedstocks, there is an optimal temperature window where oil yield is maximised under FGAP (typically 480–530 °C). Above this, steam and CO_2 reforming of oil vapours dominates and gas yield increases at the expense of liquid. The optimal temperature window for PET and mixed plastics is shifted to a lower temperature of 450–500 °C due to the lower thermal stability of the ester bonds and the risk of over-decarboxylation. The char yield under FGAP was lower than that under N_2 for all plastics studied, with reductions ranging from 0.5 wt% (PS) to 8.6 wt% (PET). This has important implications for waste minimisation and reactor cleaning frequency.

Table 2. Pyrolysis product yields (wt%) for major plastic types under N_2 versus simulated flue gas (FGAP: ~10 vol% CO_2 , ~15 vol% H_2O , balance N_2) atmosphere at near-optimal temperatures. Data from original experimental studies only.

Plastic (Temp.)	Atm.	Oil (wt%)	Gas (wt%)	Char (wt%)	Key Observations	Ref.
HDPE (500 °C)	N_2	78.2	18.7	3.1	Predominantly C_{12} – C_{25} wax-range hydrocarbons; char mainly carbonaceous coke.	[42]
HDPE (500 °C)	FGAP	86.6	12.0	1.4	Oil +8.4 wt%; char –1.7 wt%; oil enriched in lighter C_8 – C_{15} fraction; gas CO elevated.	[38]
LDPE (500 °C)	N_2	80.1	16.2	3.7	Similar wax-range distribution to HDPE; moderate gas fraction.	[33]
LDPE (500 °C)	FGAP	85.5	12.4	2.1	Oil +5.4 wt%; char –1.6 wt%; olefin content of gas increased; H_2 elevated by steam.	[33]
PP (500 °C)	N_2	81.4	15.3	3.3	Oil rich in C_5 – C_{11} alkenes; some branched isomers from β -scission.	[4]
PP (500 °C)	FGAP	88.6	9.8	1.6	Oil +7.2 wt%; increased aromatics at higher T; olefin/paraffin ratio higher under CO_2 .	[26]
PS (500 °C)	N_2	82.7	9.1	8.2	Oil dominated by styrene (>60 wt%); char from condensed aromatic residues.	[27]
PS (500 °C)	FGAP	83.4	11.2	5.4	Minor oil increase; char reduced by 2.8 wt%; steam suppresses PAH formation.	[35]
PET (500 °C)	N_2	42.3	43.2	14.5	Liquid contains benzoic acid and terephthalic acid; gas rich in CO_2 and CO .	[28]
PET (500 °C)	FGAP	39.6	54.6	5.8	Liquid lower in wt% but enriched in monomeric species; char –8.6 wt%; H_2 elevated.	[34]
Mixed† (500 °C)	N_2	74.6	19.4	6.0	Mixed PE/PP/PS (60/25/15 wt%); oil has broad C_5 – C_{30} distribution.	[43]
Mixed† (500 °C)	FGAP	80.2	15.1	4.7	Oil +5.6 wt%; char –1.3 wt%; improvement attenuated vs. pure polyolefins due to mixed feedstock effects.	[43]

**Figure 2.** (a) Comparison of oil yield (wt%) for major plastic types under N_2 and flue-gas atmosphere pyrolysis (FGAP) at 500 °C. (b) Effect of pyrolysis temperature (400–650 °C) on product distribution (oil, gas, char) for HDPE under FGAP conditions, with the optimal operating window at 480–520 °C highlighted. Data from [26], [27], [32]–[35], [38], [43].

Reactor Design and Integration Configurations

The practical coupling of MSW incineration and plastic pyrolysis requires coupled reactor systems, where the incinerator flue gas acts as a heat carrier and reactive atmosphere for the downstream pyrolysis unit. Several coupling configurations have been proposed and in some cases demonstrated at pilot scale [43].

The simplest configuration is direct gas injection, where partially cleaned flue gas (after the boiler, after the cyclone, temperature ~250–400 °C) is directly injected into the plastic pyrolysis reactor, which is typically a screw-conveyor or fixed-bed reactor. The driving force for the thermal degradation is the temperature difference between the hot gas and the plastic feedstock. This method is thermally efficient, but exposes the pyrolysis reactor and downstream condensation equipment to the full spectrum of flue gas contaminants (SO_2 , HCl, PM, PCDD/F), increasing corrosion risk and requiring more aggressive product-gas cleaning [44]. This concept was demonstrated by Lim et al. [43], who developed a pilot-scale flue gas pyrolysis system for organic and plastic wastes (OPW) using a fast oxidative pyrolysis approach with a non-thermal plasma (NTP) reactor for product upgrading. The system operated at a pyrolysis temperature of 350 °C using flue gas as the pyrolysis agent, and the addition of a small percentage of plastics was found to increase the liquid yield. The use of flue gas significantly reduced operational costs and lifecycle carbon emissions compared to conventional nitrogen-based pyrolysis systems [43].

The indirect heat-exchange configuration inserts a shell-and-tube or plate heat exchanger between the incinerator flue gas duct and the process gas stream of the pyrolysis reactor. The heat transfer between the two streams occurs without the gases being in direct contact. A synthetic gas mixture, similar in composition to the flue gas but free of contaminants, is circulated through the pyrolysis reactor; this strategy decouples heat integration from gas composition and allows independent optimisation of the pyrolysis atmosphere. The major drawback is the energy penalty in the heat exchanger (typically 10–20 °C approach temperature, i.e., less driving force) and the additional capital expenditure [45].

Rotary kiln pyrolysis reactors are particularly well suited for integration with MSW incineration as most industrial incinerators already use the rotary kiln technology in at least one stage of the process. Plastic pyrolysis using a second rotary kiln downstream of the primary incineration kiln allows gravity-fed plastic feeding, shared structural foundations, and direct transfer of gases through insulated refractory-lined ducts. Ariyaratne et al. [46] characterized in detail the transport behavior and heat distribution in rotary kilns by studying axial mixing of solids and thermal profiles in pilot-scale kilns relevant to waste pyrolysis applications. The inclination angle and rotation speed can be used to control the residence time of the reactor, allowing for flexibility in processing heterogeneous plastic waste streams. However, scale-up presents challenges in maintaining uniform temperature distribution along the kiln axis and in controlling axial gas dispersion that may cause incomplete pyrolysis in cool zones.

Fluidized-bed pyrolysis reactors (bubbling or circulating) provide excellent gas-solid contact, uniform temperature distribution and high heat transfer rates. These are beneficial for the FGAP operation as the reactive gas (CO_2 /steam) needs to contact the pyrolysing plastic particles efficiently to exert its chemical effect. Kaminsky et al. [47] operated a fluidized-bed pilot unit at 500–600 °C on HDPE and PP feedstocks using nitrogen. Later adaptation of similar units to CO_2 -enriched atmospheres by other groups showed 4–10 wt% oil yield improvement in line with trends of Table 2 [48]. A primary design challenge for fluidized-bed FGAP is to prevent sintering of silica or alumina sand bed due to alkali chlorides (NaCl, KCl) that can co-deposit with PM in partially cleaned flue gas [22].

The plasma-assisted and microwave-enhanced pyrolysis configurations have also been investigated for their ability to intensify FGAP reactions at lower bulk temperatures [49]. Microwave pyrolysis under a CO_2 atmosphere has been shown to give higher gas yields (particularly H_2 and CO) than conventional heating under CO_2 , due to selective heating of polar sites and the char acting as a microwave receptor. These configurations are energy intensive at present but could find niche applications in the production of high-value chemicals from specific plastic fractions, such as PET [49].

Environmental and Safety Considerations

The environmental acceptability of integrated incineration-pyrolysis systems is critically dependent on the management of chlorinated organic pollutants, especially polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F), and on robust hydrogen chloride (HCl) abatement. These issues are more important for FGAP than for conventional pyrolysis because the hot gas stream may carry chlorine precursors from the incinerator into the pyrolysis environment and possibly catalyse *de novo* synthesis of chlorinated compounds under the temperature and pressure conditions of the pyrolysis reactor.

PCDD/F formation in MSW incineration systems is well characterised: high-temperature gas-phase formation above 800 °C (via chlorobenzene and chlorophenol precursors) and lower-temperature (250–450 °C) *de novo* synthesis on catalytic fly-ash surfaces mediated by copper chloride ($CuCl_2$) are the primary pathways

[50]. The temperature window of 250–450 °C corresponds exactly to the ideal working window for plastic pyrolysis in FGAP. This raises the concern that fly-ash particles entrained in the pyrolysis reactor might catalyze PCDD/F formation in the presence of organic precursors from plastic degradation. For WtE plants, the stack PCDD/F ELV of 0.1 ng TEQ/Nm³ is set by EU IED 2010/75/EU [21]. Thus, an integrated FGAP system must ensure that any flue gas employed as pyrolysis atmosphere is sufficiently denuded of PM (below the IED limit of 10 mg/Nm³) to avoid fly-ash-catalysed PCDD/F reformation. Rapid quenching of the product gases from pyrolysis below 200 °C is also important to avoid memory-effect re-formation upon condensation [51].

HCl in the pyrolysis atmosphere is a double-edged sword: equipment corrosion and product contamination. Under the temperatures and reducing conditions of plastic pyrolysis, HCl can chlorinate aromatic intermediates (from PS or PET pyrolysis) to form chlorobenzenes and chlorophenols, which are regulated as precursors of PCDD/F. Operational mitigation strategies include upstream HCl scrubbing (wet or dry injection of Ca(OH)_2) to reduce HCl to less than 50 mg/Nm³ before gas enters the pyrolysis reactor, and the use of corrosion-resistant reactor materials (Inconel alloys, SiC-coated surfaces) [52]. However, this creates an additional SO_2 management burden [53]. Injection of sulphur compounds (e.g., $(\text{NH}_4)_2\text{SO}_4$) has been suggested as a PCDD/F inhibitor because SO_2 competes with Cl for active catalytic sites on fly ash.

Also, the management of solid residues (char and ash) after pyrolysis requires regulatory attention. Mixed plastics char from FGAP may contain heavy metals (from incinerator fly ash carry-over), PAH adsorbed from the pyrolysis atmosphere, and residual chlorine. Yek et al. [54] demonstrated that co-injection of steam at 500 °C into the FGAP reactor reduced char PAH content compared to a CO_2 -only atmosphere, which was attributed to steam-mediated oxidative ring-opening of condensed aromatics [54]. In addition to product quality, the integrated system must also deal with occupational health risks related to start-up and maintenance. Closed-loop condensate handling is required to prevent flash fires from the accumulation of hydrocarbon vapour-air mixtures, alongside continuous vapour monitoring and nitrogen blanketing of oil storage vessels [50].

Techno-Economic Assessment

Techno-economic assessment (TEA) of integrated incineration-pyrolysis systems is still in its infancy, and the following estimates are based on published TEA studies of standalone pyrolysis plants and partial integration analyses. They are indicative rather than definitive and are known to vary significantly by region, feedstock composition, energy prices, and regulatory environments [41], [43]. To ensure transparency, numerical figures cited in this section that are derived from peer-reviewed experimental or engineering studies are identified with their original reference; figures described as “estimated” or “projected” are indicative extrapolations from analogous systems and should not be interpreted as validated results for fully integrated FGAP plants. No commercial-scale integrated FGAP facility has yet been reported in the literature, and all economic projections carry substantial uncertainty pending long-duration pilot demonstration data.

The capital expenditure (CAPEX) for a standalone plant for plastic pyrolysis of 20,000 tonnes per year has been reported to be in the range of USD 4–12 million (USD 200–600 per tonne of annual capacity), depending on reactor technology, degree of automation, and downstream oil-refining requirements [3]. Integration with an existing MSW incineration plant at the same site eliminates the cost for a separate flue gas boiler and gas-cleaning train for the pyrolysis unit, potentially reducing the CAPEX by 15–30% [43]. On the other hand, retrofitting the existing incinerator gas handling system to divert and meter a portion of the hot flue gas to the pyrolysis reactor would add capital costs estimated at USD 0.5–2 million for gas ducting, valves, instrumentation, and safety interlocks [44]. The net CAPEX benefit of integration is small at a small scale (less than 10,000 t/y plastic) but becomes more significant at larger scales due to the economies of shared infrastructure.

The OPEX savings from the integration of FGAP can be mainly attributed to two effects: (i) decreased external heating energy to the pyrolysis reactor, and (ii) avoided tipping fees for plastic waste that would otherwise need to be disposed of by other means. For a system in which hot flue gas at 350 °C is used as the primary heat carrier for pyrolysis at 500 °C, heating requirements are reduced by an estimated 20–35% compared to an externally fired pyrolysis unit, corresponding to annual energy cost savings of USD 80,000–200,000 per 10,000 tonnes-per-year capacity at European natural gas prices (2023 basis) [45]. Plastic waste gate fees in Europe were in the range of EUR 60–150/tonne in 2022–2023 [5], corresponding to a tipping-fee revenue stream of EUR 0.6–1.5 million/year for a 10,000 tonne/year facility. In combination with the revenues from pyrolysis oil (estimated USD 450–700 per tonne of oil at 2023 fuel oil market prices), the integrated system generates an estimated gross revenue of USD 2.5–4.5 million per year for a 10,000 tonne-per-year facility, indicating a simple payback period of 3–6 years under favourable conditions [3], [41].

In all the TEA studies available, sensitivity analysis shows that the quality of the feedstock (variation in oil yield of ± 10 wt% between clean and contaminated plastic streams), the price of oil in the market, and the value of carbon credits are the main drivers of the project economics [41]. The implementation of carbon pricing under

the EU Emissions Trading System (ETS), currently around EUR 50–90 per tonne CO_2 equivalent in 2023 [5], could be another source of revenue if the integrated system shows validated CO_2 abatement compared to both the landfill baseline and standalone incineration. However, the carbon accounting methodology for hybrid systems is not yet standardized.

The findings of this review have important implications for policymakers and industrial operators. At the policy level, the existing WtE regulatory frameworks in Europe (mainly EU IED 2010/75/EU [21] and the EU Waste Framework Directive) do not explicitly consider hybrid incineration-pyrolysis configurations, which generates regulatory ambiguity concerning emission monitoring obligations, permitting requirements, and product (pyrolysis oil) classification. Regulatory agencies should develop technology-neutral regimes for hybrid WtE-pyrolysis plants that include specific requirements for emission monitoring and guidance on the classification of pyrolysis oil as a chemical feedstock or as a fuel. Incentive mechanisms such as EPR schemes that credit chemical recycling outputs or WtE feed-in tariff adjustments for integrated systems could help accelerate commercial deployment. At an industry level, co-processing of pyrolysis oil by petrochemical companies in steam crackers should consider co-location and off-take agreements with WtE operators to enable a stable feedstock supply and revenue certainty for integrated FGAP investments.

Current Challenges and Research Gaps

Despite the encouraging experimental evidence reviewed above, several important technical, operational, and knowledge gaps remain to be addressed before integrated incineration-pyrolysis systems can be deployed at a commercial scale.

Heat exchanger fouling is one of the most operationally critical challenges. In direct-contact FGAP configurations utilizing partially cleaned flue gas, the hot-gas duct and heat-exchange surfaces are exposed to residual PM, fly ash, condensed heavy metals, and sticky organic aerosols. Deposition of alkali metal chlorides (NaCl, KCl) on the surface of heat exchangers at temperatures of 300–600 °C leads to the formation of a eutectic melt layer, which causes an increase in the corrosion rate of the tube walls and a reduction in the heat transfer coefficients by up to 40% during several hundred hours of operation [22]. This requires either aggressive upstream PM reduction (to less than 1 mg/Nm³) or periodic automated sootblowing and chemical cleaning regimes, which increase OPEX. No long-duration pilot study beyond 500 hours of continuous FGAP operation has been published in the peer-reviewed literature, representing a significant gap in operational durability data.

Catalyst poisoning induced by HCl and SO_2 is a major challenge for catalytic FGAP. Zeolite catalysts that may significantly improve oil quality are rapidly deactivated by HCl through competitive adsorption on Brønsted acid sites and by SO_x through sulphation of the alumina framework [36]. Even with upstream scrubbing to less than 50 mg/Nm³ HCl, long-term cumulative chlorine loading leads to a progressive reduction in catalyst activity. Up to now, catalyst lifetimes longer than 24 h under realistic FGAP conditions have not been reported in the literature, and the development of HCl-tolerant catalysts (sulphated zirconia, phosphate-modified zeolites, metal oxide mixed catalysts) remains an active area requiring systematic evaluation [29], [36].

Real-time monitoring and control of flue gas composition is a formidable instrumentation problem. The composition of MSW incinerator flue gas varies with the waste load variability (daily and seasonal), combustion instability, and gas cleaning efficiency. The CO_2 content can vary from 6 to 16 vol% and the steam content from 8 to 22 vol% within one single operating day [6], [7]. If not actively compensated, such fluctuations can lead to variable pyrolysis conditions and hence inconsistent product quality. Contemporary inline gas analysers (NDIR, FTIR) offer adequate measurement of CO_2 and steam but are not sufficiently fast and reliable for robust feedback control at the time resolution required for pyrolysis product quality management. Advanced sensor arrays and chemometric data processing are needed to bridge this gap.

Scale-up risk is inherent in translating bench-scale or pilot-scale FGAP results to industrial systems. During the volumetric scale-up of pyrolysis reactors from bench (0.1–1 kg/h) to commercial (1–10 tonne/h), problems with uniform heat distribution, control of gas-solid contact time, and management of product vapour residence time are encountered, which are hard to predict from laboratory data alone [46]. Non-linear scale effects, such as changes in bubble size or gas distribution in fluidized-bed reactors, or axial temperature gradients and the degree of fill in rotary kilns, can cause significant effects on product distribution, but are not accounted for by the Damköhler-number scale-up. Pilot-scale campaigns with throughputs greater than or equal to 100 kg/h for at least 1,000 hours of continuous operation are needed to generate the reliability data necessary for commercial investment decisions. Such datasets are not available in the peer-reviewed public literature at this time.

The peer-reviewed literature contains very little life-cycle assessment (LCA) data for integrated systems. The limited published LCA studies on plastic pyrolysis systems rely on hypothetical configurations and generic emission factors instead of operational data from actual FGAP systems, which limits the confidence in environmental impact conclusions [2]. Standardised definitions of system boundaries, allocation methods for the

shared utilities (heat, steam, electricity) between the incinerator and pyrolysis unit, and primary operational emission data are urgently needed.

Future Perspectives

Several emerging technological and methodological trends will likely enable, or have initial empirical support for enabling, the development and deployment of integrated incineration-pyrolysis systems in the circular economy landscape. Where the discussion below draws on findings from peer-reviewed studies of related (but not FGAP-specific) systems, this is noted explicitly; projections specific to FGAP integration remain prospective and have not yet been validated at the pilot scale.

Artificial intelligence (AI) and machine learning (ML) can revolutionise the predictive control of FGAP systems. The nonlinear multivariable character of coupled incineration-pyrolysis operations—with simultaneous changes in flue gas composition, temperature, flow rate, and plastic feedstock composition—renders rule-based control inadequate for optimising product quality. Recurrent neural networks and gradient-boosted models trained on online sensor data (temperature profiles, gas-phase IR spectra, online gas chromatography) have been shown to predict product yields within 3 wt% for standalone pyrolysis systems [8] and could be extended to FGAP with appropriate training datasets. An advanced frontier that could facilitate autonomous optimisation of the oil yield and quality in response to changing flue gas conditions involves reinforcement learning techniques, where an AI agent learns optimal control policies by interacting with the process in simulation or in reality.

Digital twin (DT) technology, consisting of high-fidelity computational models of physical systems that are calibrated and updated with real-time sensor data, provides a complementary framework for the operational management of integrated FGAP plants. A DT of the integrated system would consist of kinetic pyrolysis models (Arrhenius-based or molecular-level mechanistic models), computational fluid dynamics (CFD) of the reactor geometry, and flue gas composition propagation models, enabling real-time scenario analysis, fault detection, and optimisation without physical experimentation. Ding et al. [40] pioneered DT implementations for standalone pyrolysis, showing reductions in off-specification product events compared to manually controlled operations. Analogous systems for FGAP would represent a major advance.

Probably the most important short-term research priority is the development of contaminant-tolerant catalysts. Several catalyst chemistries have shown initial promise in simulated acid-gas conditions: phosphate-intercalated layered double hydroxides (LDH) retain greater than 70% of fresh activity after 48 hours at 50 mg/Nm³ HCl in a fixed-bed configuration [29]; cerium oxide-modified nickel-alumina catalysts are resistant to sulphur poisoning via SO_x -oxidising redox cycles [30]; and micro-mesoporous hierarchical zeolites with enhanced external surface areas present accessible active sites less susceptible to pore-mouth blockage by condensed chlorinated products [36]. A systematic lifetime test under real FGAP conditions is a high-priority research need for these materials.

The circular economy aspect of integrated FGAP is more than the recovery of energy and materials. Mixed plastic waste pyrolysis oil can be used as a chemical feedstock (“pyrolysis oil as a naphtha substitute”) for steam crackers, thus enabling a circular route from end-of-life plastic to new plastic without the quality constraints of mechanical recycling. Several large petrochemical companies have announced commitments to co-process pyrolysis oil in existing crackers [3], and integration with WtE facilities could provide a geographically concentrated, scalable supply of pyrolysis oil feedstock.

The CO_2 -rich flue gas fraction can be further valorised by carbon capture and utilisation (CCU). Instead of using all flue gas as a pyrolysis atmosphere, some could be diverted for post-combustion CO_2 capture (using amine scrubbing or solid sorbents) and the captured CO_2 redirected as a high-purity pyrolysis atmosphere without HCl and PM contaminants. The CCU-FGAP hybrid will simultaneously reduce net CO_2 emissions from the WtE facility and provide a clean, composition-controlled reactive gas for pyrolysis. Its economic viability is linked to the cost of CO_2 capture (USD 40–80 per tonne CO_2 for post-combustion capture at WtE scale today) and carbon market prices [5].

CONCLUSIONS

The conclusion section contains the main points of the articles. This systematic review has synthesised evidence from 60 peer-reviewed studies to evaluate the integration of MSW incineration with plastic waste pyrolysis using incinerator flue gas as a reactive atmosphere and heat carrier. The following main conclusions are derived:

First, the reactive constituents of MSW incinerator flue gas, CO_2 and steam, have different and in some cases synergistic effects on the distribution of plastic pyrolysis products. CO_2 favours mild cracking reactions to

produce light hydrocarbons, while steam acts as a hydrogen donor to prevent char formation and can increase oil yield at optimal temperatures (480–520 °C for polyolefins). Pyrolysis in a combined flue-gas atmosphere (FGAP) gives an increase of 5–15 wt% in polyolefin oil yield compared to conventional N_2 pyrolysis, representing a substantial increase in liquid fuel yield.

Second, the type of plastic greatly affects the magnitude and direction of FGAP effects. Polyolefins (HDPE, LDPE, PP) exhibit the greatest increase in oil yield, while PS shows a modest increase. PET shows a qualitatively different response, yielding a lower oil weight percentage but a higher-value monomeric product composition. Mixed plastics show attenuated but positive overall effects.

Third, reactor design and integration configurations are critical determinants of process performance. Rotary kiln and fluidized-bed pyrolysis reactors appear to offer the best potential for the integration of FGAP with incinerator facilities, provided that heat exchanger fouling and fly-ash contamination are eliminated by suitable upstream gas cleaning. Direct flue gas injection offers the best thermal efficiency but carries the highest risk of contamination. Indirect heat exchange configurations sacrifice some energy efficiency for improved product quality control.

Fourth, environmental and safety management must be integrated into the system design. At temperatures of 250–450 °C, which are optimal for pyrolysis, there is a risk of PCDD/F formation; therefore, fly ash must be removed rigorously before the flue gas enters the pyrolysis reactor. Managing HCl is important to protect equipment and maintain product quality. At all stages of the integrated process chain, emission limits according to the European Union (EU) Industrial Emissions Directive (2010/75/EU) must be met.

Fifth, the techno-economic outlook is positive for integrated systems, with simple payback periods of 3–6 years estimated for European market conditions. This viability is driven by tipping fee revenues, energy cost savings from the integration of flue gas heat, and pyrolysis oil sales. However, long-duration operational data, standardised carbon accounting, and commercial-scale demonstrations are needed to reduce investment risk and enable wider deployment.

The main research gaps identified are: (i) pilot-scale FGAP operational data for a long duration exceeding 1,000 hours; (ii) HCl-tolerant catalyst development and lifetime testing under real flue gas conditions; (iii) real-time flue gas monitoring and AI-based control systems; (iv) robust life-cycle assessment studies using operational data; and (v) standardised system boundary protocols for carbon accounting in hybrid WtE-pyrolysis facilities. Regulatory frameworks specifically accommodating integrated WtE-pyrolysis configurations are also needed. Bridging these gaps will be critical if FGAP technology is to make a meaningful contribution to the transition to a circular economy in plastic waste management.

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