EQA - International Journal of Environmental Quality
ISSN 2281-4485 - Vol. 74 (2026): 88 - 99
Journal homepage: https://eqa.unibo.it/

published by

Environmental benefits of biomass–plastic co-pyrolysis bio-oil in diesel engines: waste valorization, emission reduction, and sustainability

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Article info
Received 10/4/2026; received in revised form 8/6/2026; accepted 3/8/2026
DOI: 10.60923/issn.2281-4485/24698

Abstract
The growing generation of biomass residues and plastic waste, together with the environmental impact of fossil fuel combustion, has intensified research into sustainable alternative fuels for compression ignition engines. This review critically evaluates the environmental benefits of using bio-oil derived from co-pyrolysis of biomass and waste plastics as a partial diesel substitute. Co-pyrolysis synergistically combines oxygen-rich biomass with hydrogen-rich plastics, producing hydrocarbon-enriched bio-oil with significantly improved fuel properties compared to conventional biomass-derived pyrolysis oil. Analysis of 41 peer-reviewed studies shows that co-pyrolysis bio-oil has higher heating values (34–47 MJ/kg), lower oxygen content (2.6–15.2 wt%), and reduced acidity. When blended with diesel at 10–30 vol%, these oils give brake thermal efficiencies of 27–34%, approaching or exceeding diesel, while substantially reducing CO (up to 40%), HC (up to 61%) and smoke opacity. NOx emissions show variable trends (-6% to +25%), depending on feedstock and engine conditions. Catalytic co-pyrolysis with ZSM-5, dolomite or activated carbon further improves deoxygenation and aromatic hydrocarbon selectivity. Exergy and sustainability analyses show that co-pyrolysis oil blends improve sustainability indices (1.34–1.43) and reduce exergy destruction compared to neat diesel. Despite challenges in fuel stability, NOx trade-offs and feedstock variability, biomass-plastic co-pyrolysis bio-oil represents a viable waste-to-fuel pathway that simultaneously addresses waste management crises and reduces dependence on fossil diesel.

Keywords: *Co-pyrolysis; Bio-oil; Waste plastics; Compression ignition engine; Environmental benefits; Sustainability*

Introduction

Global energy demand continues to rise, driven by population growth, industrialization and increasing transportation needs. Fossil fuels currently supply about 81.5% of global energy consumption (Lv et al., 2026; Padhy et al., 2025). Daily worldwide oil consumption reaches approximately 94.67 million barrels, with resources depleting faster than natural replenishment (Padhy et al., 2025). Simultaneously, greenhouse gas emissions from fossil fuel combustion have more than doubled from 24.5 $GtCO_2eq$/year in 1970 to 50.9 $GtCO_2eq$/year in 2020 (Mikulski et al., 2020). These converging crises of resource depletion and environmental degradation demand urgent development of sustainable, renewable alternatives. Parallel to energy concerns, solid waste management presents another critical environmental challenge. Global plastic production reached 367 million tons in 2020, with projections exceeding 650 million tons annually by 2050 (Lv et al., 2026). In India alone, about 9.4 million tonnes of plastic waste is generated annually, of which only 60% is recycled, leaving large quantities for landfilling or environmental release (Padhy et al., 2025). Simultaneously, biomass residues – agricultural waste, forestry residues and food processing by-products – represent abundant, renewable carbon sources

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DOI: 10.60923/issn.2281-4485/24698

that are often underutilised or burned in the open, causing air pollution (Shadangi and Mohanty, 2014; Hassan et al., 2016). Pyrolysis, the thermal decomposition of organic materials in oxygen-free atmospheres, has emerged as a promising thermochemical conversion technology capable of transforming both biomass and plastic waste into valuable liquid products (pyrolysis oil or bio-oil), syngas and char (Bridgwater, 2012; Venderbosch and Prins, 2010). However, biomass - derived bio-oil suffers from high oxygen content (35-60 wt%), high water content (15-30 wt%), low pH (2-4) and low heating value (15-20 MJ/kg), rendering it unsuitable for direct application in CI engines (Zhang et al., 2007; Oasmaa et al., 2010; Lv et al., 2026). Conversely, plastic-derived pyrolysis oil exhibits high heating values (41-47 MJ/kg) and a hydrocarbon-rich composition but may contain chlorine, sulphur and heavy metal contaminants (Demirbas, 2007; Lv et al., 2026; Alawa and Chakma, 2022). Co-pyrolysis – the simultaneous pyrolysis of two or more feedstocks – exploits synergistic interactions between oxygen-rich biomass and hydrogen-rich plastics. This approach enhances deoxygenation, increases hydrocarbon yield and improves bio-oil quality while simultaneously addres-sing two waste streams (Zhou et al., 2014; Shadangi and Mohanty, 2014; Hassan et al., 2016; Alawa and Chakma, 2022). The resulting co-pyrolysis bio-oil, after appropriate upgrading or blending, shows considerable promise as a partial diesel substitute in CI engines. This review critically synthesises the current literature on biomass--plastic co-pyrolysis bio-oil as a diesel substitute, with emphasis on environmental benefits. Key objectives include: (1) characterising suitable feedstocks and co-pyrolysis mechanisms, (2) evaluating bio-oil properties and production parameters, (3) assessing engine performance and emission characteristics, (4) quantifying environmental benefits through exergy and sustainability analyses, and (5) identifying challenges and future research directions.

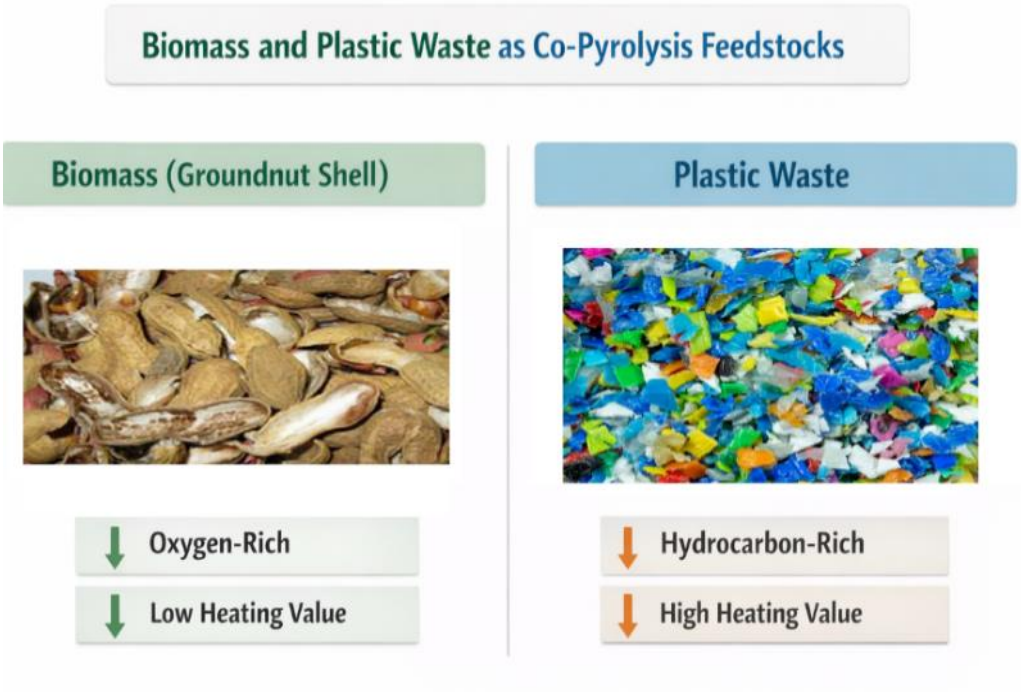

Figure 1
Biomass and plastic waste as co-pyrolysis feedstocks

Materials and methods

This review follows a systematic literature synthesis approach. A comprehensive search was conducted in Scopus, Web of Science and Google Scholar using keywords: "co-pyrolysis", "biomass and plastic", "bio-oil", "diesel engine", "emissions" and "environmental benefits". Studies published between 2010 and 2026 were considered. Only peer-reviewed articles reporting original experimental data on co-pyrolysis of lignocellulosic biomass with waste plastics (PE, PP, PS, PET, PVC) and subsequent engine performance or emission characterisation were included. In total, 41 primary studies were analysed. Data on feedstock properties, pyrolysis conditions, bio-oil characteristics, engine performance (BTE, BSFC) and emissions (CO, HC, NOx, smoke) were extracted and synthesised qualitatively and quantitatively where possible.

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Results

Biomass feedstock characteristics

Biomass repre-sents the world's largest sustainable energy source, with about 220 billion tons of dry biomass produced an-nually (Hassan et al., 2016). Biomass is classified into three generations based on biofuel production poten-tial: first-generation (edible crops), second-generation (lignocellulosic biomass, agricultural residues) and third -generation (algal biomass) (Lv et al., 2026; Hassan et al., 2016). The chemical composition of bio mass fundamentally determines -its pyrolysis behaviour and bio-oil characteristics. Lignocellulosic biomass compri-ses three primary components: cellulose (30-50%), hemicellulose (15-35%) and lignin (10-20%) (Lv et al., 2026; Rajamohan and Kasimani, 2018). Cellulose and hemicellulose decompose at lower temperatures (200 - 400 °C), producing anhydrosugars, furans and light oxygenates, while lignin, with its aromatic structure and higher thermal stability, decomposes at higher temperatures (>500 °C), yielding phenolic compounds (Sharma et al., 2015; Lv et al., 2026; Alawa and Chakma, 2022).

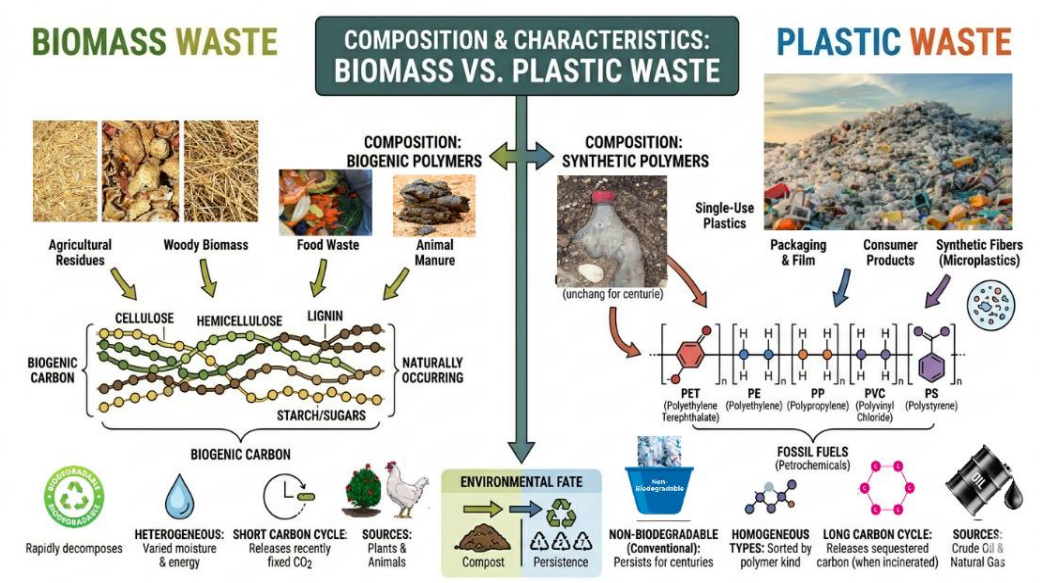

Figure 2
Composition and characteristics of biomass vs plastic waste

Proximate and ultimate analyses provide critical feedstock characterisation. Table 1 summarises representative biomass feedstocks investigated in co-pyrolysis studies. Volatile matter content, typically 52-89 wt%, strongly correlates with bio-oil yield potential. Fixed carbon (10-33 wt%) influences char formation, while ash content (0.2-43 wt%) affects catalytic activity and reactor fouling (Lv et al., 2026; Rajamohan & Kasimani, 2018). High ash content in rice husk (36.5 wt%) and certain macroalgae significantly influences pyrolysis product distribution and char characteristics (Lv et al., 2026; Ebadi et al., 2025).

Table 1. *Proximate and ultimate analysis of representative biomass feedstocks*

Biomass type	Volatile (wt%)	Fixed C (wt%)	Ash (wt%)	C (wt%)	H (wt%)	O (wt%)	HHV (MJ/kg)	Reference
Poplar	89.2	10.9	—	46.7	6.2	—	18.8	Lv et al., 2026
Pine	75.3	23.1	0.6	52.2	5.1	—	—	Lv et al., 2026
Rice straw	68.7	25.0	—	—	—	—	—	Lv et al., 2026
Groundnut shell	79.8	9.7	1.8	57.6	7.6	30.4	—	Kumar et al., 2024
Calophyllum seed cake	72.6	21.1	2.7	43.8	6.3	45.9	18.8	Rajamohan and Kasimani, 2018
Banana peel	—	—	—	55.6	9.7	11.0	—	Kumar et al., 2024
Spirulina (algae)	75.5	11.2	3.2	64.2	6.9	27.6	20.2	Lv et al., 2026

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DOI: 10.60923/issn.2281-4485/24698

The high oxygen content (typically 30–50 wt%) and low H/C ratio (0.3–1.7) of biomass contribute to the oxygenated nature of conventional bio-oil. However, certain biomasses with higher lipid content, such as microalgae and some non-edible seeds, offer improved hydrogen-to-carbon ratios and reduced oxygen content [24,38].

Plastic waste feedstock characteristics

Global plastic production grew from 1.5 million tonnes in 1950 to 359 million tonnes in 2018 (Alawa and Chakma, 2022). Plastics are classified into thermoplastics and thermosets, with thermoplastics – including PET, HDPE, PVC, LDPE, PP and PS – dominating waste streams (Miandad et al., 2016; Lv et al., 2026; Alawa & Chakma, 2022). Table 2 presents the characteristics of common waste plastics relevant to co-pyrolysis. Polyolefins (LDPE, HDPE, PP) exhibit excellent fuel potential with high volatile matter (>95 wt%), high carbon (84-92 wt%) and high hydrogen (7.8-15.3 wt%) contents, resulting in HHV values of 39-47 MJ/kg (Lv et al., 2026; Alawa and Chakma, 2022). These plastics serve as effective hydrogen donors during co-pyrolysis, promoting deoxygenation of biomass-derived oxygenates (Zhou et al., 2014; Alawa and Chakma, 2022; Hassan et al., 2016). However, plastics containing heteroatoms present challenges. PVC releases corrosive hydrogen chloride (HCl) during pyrolysis, necessitating dechlorination strategies (Lv et al., 2026; Hassan et al., 2016). PET, despite its high oxygen content, can enhance decarboxylation reactions during co-pyrolysis. Real-world plastic waste often contains additives (plasticisers, colorants, stabilisers) and contaminants that may affect product quality and catalyst performance (Miandad et al., 2016; Lv et al., 2026).

Table 2. *Characteristics of common waste plastics for co-pyrolysis*

Plastic	Volatile (wt%)	C (wt%)	H (wt%)	O (wt%)	Cl (wt%)	HHV (MJ/kg)	Degradation temp (°C)	Reference
LDPE	99.8	85.8	14.0	—	—	46.4	330	Fakhri Hoseini et al. 2013; Lv et. al.2026
HDPE	97.2	86.5	15.1	—	—	44.0	340	Sharma et al., 2015
PP	96.9	84.7	15.3	—	—	45.1	300	Sharma et al., 2015
PS	99.6	92.4	7.8	—	—	39.8	360	FakhriHoseini & Dastanian, 2013
PET	94.4	62.6	4.4	33.0	—	22.0	380	Onwudili et al., 2009
PVC	95.8	38.7	4.8	—	56.5	19.3	250	Williams et al.1999

Fundamentals of Co-Pyrolysis Technology

Pyrolysis principles and classifications. Pyrolysis is the thermochemical decomposition of organic materials at elevated temperatures (typically 300-700 °C) in an inert atmosphere (e.g., N_2, Ar) in the absence of oxygen (Sharma et al., 2015; Bridgwater, 2012; Venderbosch and Prins, 2010). The process yields three primary product fractions: liquid (bio-oil), solid (char) and non-condensable gas (syngas) (Bridgwater, 2012; Venderbosch and Prins, 2010). Based on heating rate and vapour residence time, pyrolysis is classified into slow, fast and flash pyrolysis (Lv et al., 2026; Bridgwater, 2012; Venderbosch and Prins, 2010). Slow pyrolysis (0.1-1 °C/s, >300 s residence) yields 25-35 wt% char, 25-35 wt% bio-oil and 30-40 wt% gas. Fast pyrolysis (10-200 °C/s, 0.5-10 s residence) maximises liquid yield (50-75 wt%). Flash pyrolysis (>1000 °C/s, <0.5 s) gives 60-75 wt% bio-oil but requires very fine feedstock. Microwave-assisted pyrolysis offers rapid, volumetric heating and can produce bio-oil yields of 50-60 wt% with enhanced hydrocarbon selectivity (Suriapparao et al., 2018; Dong et al., 2024).

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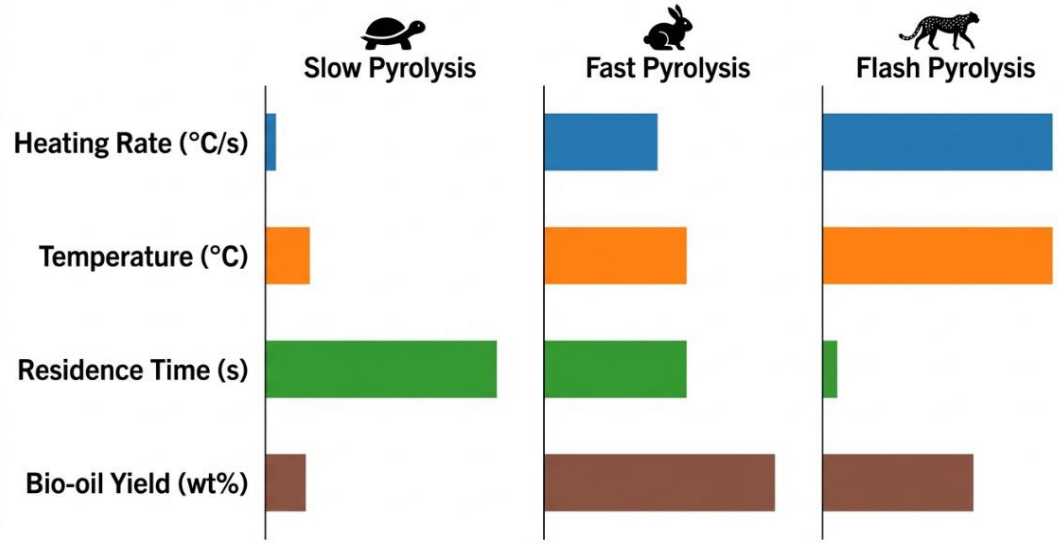

Figure 3
Comparison of pyrolysis modes

Co-pyrolysis synergistic mechanisms. Co-pyrolysis exploits synergistic interactions between different feedstocks to produce upgraded bio-oil with properties superior to additive predictions (Zhou et al., 2014; Shadangi & Mohanty, 2014; Hassan et al., 2016; Alawa and Chakma, 2022). Four primary mechanistic pathways are involved:

- Hydrogen transfer: Hydrogen-rich plastics generate reactive H* radicals that promote deoxygenation through dehydration, decarboxylation and decarbonylation (Zhou et al., 2014; Alawa and Chakma, 2022; Hassan et al., 2016).
- Radical-radical interactions: Biomass-derived radicals initiate polymer chain scission in plastics, lowering activation energy by 30-60 kJ/mol (Choudhary et al., 2023; Prasertpong et al., 2023).
- Diels-Alder cycloaddition: Biomass-derived furans react with plastic-derived olefins to produce aromatic hydrocarbons (Hassan et al., 2016).
- Hydrocarbon pool mechanism: On zeolite catalysts, oxygenated compounds are converted to olefins and aromatics within the catalyst pore structure (Hassan et al., 2016).

The magnitude of synergistic effects depends on blending ratio, plastic type and pyrolysis conditions. Zhou et al. (2014) reported that co-pyrolysis of biomass with PS and PE gave experimental oil yields 5-15% above additive values. Alawa & Chakma (2022) found that co-pyrolysis of LDPE and PP produced oil with 75-81 wt% yield and calorific values of 44-48 MJ/kg

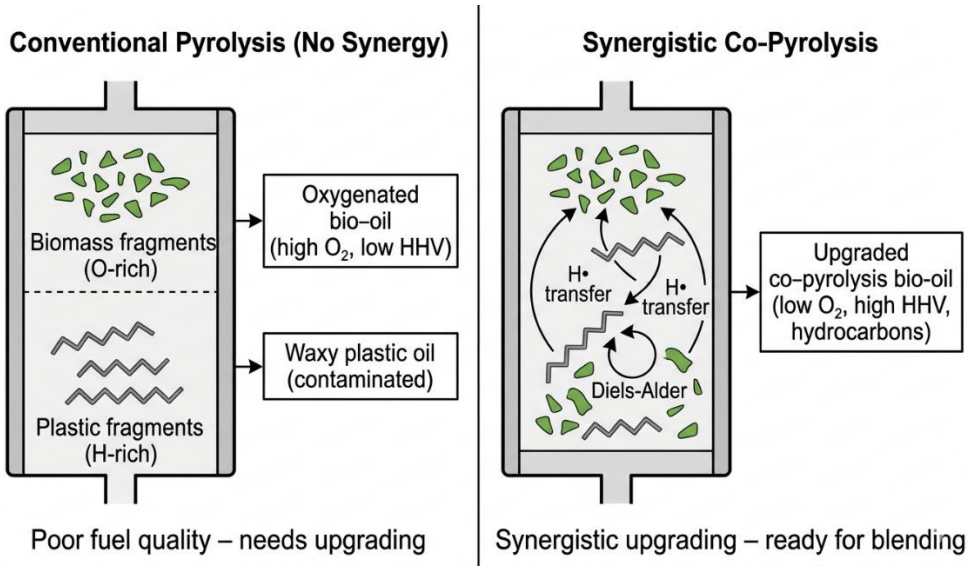

Figure 4
Comparison of reaction environments: conventional (non-synergistic) pyrolysis vs. synergistic co-pyrolysis of biomass and plastic mixtures.

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Influence of operational parameters.

- Temperature: Optimal range is 450-550 °C. Dong et al. (2024) reported maximum bio-oil yield (34.25%) from peanut shell-LDPE co-pyrolysis at 450 °C.

- Heating rate: Higher rates (50-200 °C/s) maximise liquid yields. Suriapparao et al. (2018) achieved 51-60 wt% bio-oil from PS-biomass blends using microwave heating.

- Blending ratio: Optimal biomass:plastic ratios are 1:1 to 3:1 (Zhou et al., 2014; Shadangi and Mohanty, 2014).

Bio-oil production and properties

Table 3 summarises bio-oil yields from representative studies. Co-pyrolysis bio-oil exhibits substantially improved properties compared to biomass-only bio-oil. Co-pyrolysis bio-oil exhibits substantially improved properties compared to biomass-only bio-oil. Table 4 compares the physicochemical characteristics of bio-oils from different feedstocks.

Table 3. *Bio-oil yields from biomass-plastic co-pyrolysis under various conditions*

Biomass	Plastic	Conditions	Bio-oil yield (wt%)	Reference
Peanut shell	LDPE	450 °C, Zn-ZSM-5/MCM41, microwave	34.25	Dong et al., 2024
Wood chips	HDPE/LDPE	350 °C, slow pyrolysis	80.32	Senthil et al., 2025
Ulva lactuca (algae)	PET	500 °C, 40:60 ratio	37.91	Ebadi et al., 2025
Groundnut shell	PS	450 °C, microwave, 1:1	54-60	Suriapparao et al., 2018
Rice husk	PP	450 °C, microwave, 1:1	41.1	Suriapparao et al., 2018
Calophyllum seed	PP	475 °C, 1:1	54-63	Padhy et al., 2025
LDPE + PP	—	460 °C, thermal	80.7	Alawa & Chakma, 2022
LDPE + PP	DOL/SiDOL/ZSM-5	460 °C, catalytic	63-71	Alawa and Chakma, 2023a, 2023b

Table 4. *Physicochemical properties of pyrolysis oils from different feedstocks*

Property	Biomass-only bio-oil	Plastic-only oil	Co-pyrolysis oil	Diesel
Density (g/cm³)	1.13-1.20	0.78-0.92	0.78-0.93	0.82-0.84
Viscosity @40 °C (cSt)	20-37	1.1-2.6	1.2-11.6	2.1-2.5
HHV (MJ/kg)	15-22	41-47	34-47	45-46
Oxygen (wt%)	35-50	0.2-2.0	2.6-15.2	0
Water content (wt%)	15-30	0-1	3-10	0
pH	2.5-4.0	6-7	3.5-5.5	—
Flash point (°C)	44-88	1-53	1-51	57-65
Cetane index	40-45	56-61	56-63	55-59
Sources	Zhang et al., 2007; Oasmaa et al., 2010; Lv et al., 2026; Rajamohan and Kasimani, 2018	Demirbas, 2007; Lv et al., 2026; Alawa and Chakma, 2022	Dong et al., 2024; Senthil et al., 2025; Padhy et al., 2025; Kumar et al., 2024; Alawa and Chakma, 2022	Senthil et al., 2025; Padhy et al., 2025; Singh and Paul, 2023; Rajamohan and Kasimani, 2018

DOI: 10.60923/issn.2281-4485/24698

Effect of plastic type on bio-oil quality.

- Polyolefins (LDPE, HDPE, PP): High H/C ratios yield aliphatic hydrocarbon-rich oil (C_9-C_{24}) with minimal oxygenates. Alawa & Chakma (2022) reported 65-71% paraffins, 17-26% olefins and 9-11% aromatics.
- Polystyrene (PS): Produces aromatic-rich oil (styrene, ethylbenzene, toluene). Suriapparao et al. (2018) found 48-54% aromatic hydrocarbons.
- PET: Promotes decarboxylation; Ebadi et al. (2025) reported 53-63% hydrocarbons at 500 °C.
- PVC: Requires HCl management; algae biomass can capture chlorine within the char matrix (Ebadi et al., 2025).

Catalytic upgrading. Table 5 summarises catalyst performance. Zeolite catalysts (ZSM-5) promote aromatic hydrocarbon formation. Metal-modified zeolites enhance specific pathways: Zn increases Lewis acidity (Dong et al., 2024); Ga improves BTX selectivity (Hassan et al., 2016). Dolomite-based catalysts offer cost-effective alternatives. Alawa & Chakma (2023a) reported that ZSM-5/dolomite composites achieved 67-71% liquid yields with pour points below -40 °C and calorific values up to 51.8 MJ/kg.

Table 5. *Catalyst performance in catalytic co-pyrolysis*

Catalyst	Feedstock	Key effects	Reference
Zn-ZSM-5/MCM41	Peanut shell + LDPE	68% hydrocarbons, 34% oil yield	Dong et al., 2024
HZSM-5	Cellulose + PE	50% increase in aromatics, reduced coke	Hassan et al., 2016
ZSM-5 + CaO	PP + biomass	Increased aliphatics (81%), deoxygenation	Ebadi et al., 2025
Dolomite (calcined)	LDPE + PP	Reduced viscosity, pour point <-40 °C	Alawa & Chakma, 2023a
Si-doped dolomite	LDPE + PP	Increased olefins (29%), lower hydrocarbons	Alawa & Chakma, 2023b
Ce-Fe/AC	Chlorella + HDPE	67% hydrocarbons, 51% aromatics	Ebadi et al., 2025

Bio-oil upgrading and diesel engine application

Fuel blend preparation and properties. Most studies evaluated blends with 10-30% co-pyrolysis oil by volume (B10, B20, B30). Table 6 presents blend properties. Density increases marginally with bio-oil content but remains within 810-840 kg/m³. Viscosity increases with blend ratio. Calorific value remains >40 MJ/kg for blends up to 30%. Flash point generally decreases. Cetane number (55-60) remains comparable to or exceeds diesel. Emulsification with surfactants (Span 80, Tween 80) improves stability for bio-oil contents >20% (Rajamohan and Kasimani, 2018; Das et al., 2025). Das et al. (2025) showed that distilled waste plastic oil/ethanol/diesel blends (60:20:20) improved BTE and reduced BSFC compared to unblended diesel.

Table 6. *Properties of diesel-co-pyrolysis oil blends*

Blend	Density (kg/m³)	Viscosity (cSt @40 °C)	HHV (MJ/kg)	Flash point (°C)	Cetane index	Reference
D100	820-835	2.1-2.5	45-46	57-65	55	Senthil et al., 2025; Padhy et al., 2025; Singh and Paul, 2023
B10	813-830	2.2-2.4	45.5	47-55	56-59	Padhy et al., 2025; Singh and Paul, 2023; Das et al., 2025
B20	808-816	2.3-2.6	45.7	39-52	57-60	Senthil et al., 2025; Padhy et al., 2025; Das et al., 2025
B30	803-810	2.6-3.0	45.7	34-56	56-58	Padhy et al., 2025; Singh and Paul, 2023
B40	782-803	2.9-11.6	45.8	30-34	—	Padhy et al., 2025

Engine performance – Brake thermal efficiency (BTE). Table 7 shows that co-pyrolysis oil blends achieve BTE values comparable to or slightly higher than neat diesel, especially at higher loads. The improved BTE is attributed to: (i) oxygenated compounds enhancing combustion (Senthil et al., 2025; Singh & Paul, 2023), (ii) higher cetane numbers shortening ignition delay (Padhy et al., 2025; Alawa and Chakma,

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Table 7. *Brake thermal efficiency of diesel-co-pyrolysis oil blends*

Fuel blend	Engine / load condition	BTE (%)	Change vs. diesel	Reference
B10 (wood + plastic)	Single-cylinder, 1500 rpm, full load	28.4	-4.7%	Senthil et al., 2025
B20 (wood + plastic)	Same	28.8	-2.9%	Senthil et al., 2025
B10 (PP + Calophyllum)	Same	29.4	+5.9%	Padhy et al., 2025
B30 (PP + Calophyllum)	Same	32.8	+2.3%	Padhy et al., 2025
B10 (WCO + PE)	CRDI, 1500 rpm, 3 kW, full load	33.6	+2.0%	Singh and Paul, 2023
B20 (PS + banana peel)	Single-cylinder, 1500 rpm, full load	32.8	+0.6%	Kumar et al., 2024
B10 (LDPE + PP)	VCR, 1500 rpm, full load	33.9	+4.6%	Alawa and Chakma, 2023a

2022), and (iii) improved atomisation from catalytically upgraded oils (Alawa and Chakma, 2023a, 2023b). However, Singh and Paul (2023) reported decreased BTE beyond 10% blend due to increased viscosity.

Brake specific fuel consumption (BSFC). Co-pyrolysis oil blends generally exhibit higher BSFC than diesel due to lower calorific value, but several studies report reduced BSFC for optimised blends (Senthil et al., 2025; Padhy et al., 2025; Singh and Paul, 2023; Alawa and Chakma, 2023a). Padhy et al. (2025) found that B40 achieved BSFC of 0.29 kg/kWh at full load, a 14.7% reduction vs. diesel. Singh and Paul (2023) observed BSFC reductions of 8.7-11.4% for D90P10 across loads.

Emission characteristics

Carbon monoxide (CO) emissions. Co-pyrolysis oil blends consistently reduce CO emissions compared to neat diesel, with reductions of 9-40% (Senthil et al., 2025; Kumar et al., 2024; Alawa and Chakma, 2022; Singh and Paul, 2023; Alawa and Chakma, 2023a). The mechanism involves the inherent oxygen content of co-pyrolysis oil (2.6-15.2 wt%), which promotes more complete oxidation of CO to CO_2 (Table 8).

Table 8
CO emission reduction with co-pyrolysis oil blends

Blend	Reduction vs. diesel	Load condition	Reference
B10 (wood + plastic)	20.9%	Full load	Senthil et al., 2025
B20 (PS + banana peel)	31.3%	Full load	Kumar et al., 2024
B10 (LDPE + PP)	40.4%	Full load	Alawa and Chakma, 2023a
B30 (PP + Calophyllum)	5.9%	Full load	Padhy et al., 2025
B10 (WCO + PE)	9-13%	Full load	Singh and Paul, 2023

Hydrocarbon (HC) emissions. HC emissions generally decrease by 20-61% with co-pyrolysis oil blends (Senthil et al., 2025; Kumar et al., 2024; Alawa and Chakma, 2022). Kumar et al. (2024) observed 50.7% HC reduction with B10 (PS + banana peel). Alawa & Chakma (2022) reported that B10 and B20 from LDPE-PP reduced HC by 50.7% and 21.8%, respectively. However, increased HC at low loads or high blend ratios has been noted (Padhy et al., 2025; Rajamohan and Kasimani, 2018), attributed to poor atomisation and incomplete combustion (Table 9)..

Nitrogen oxide (NOx) emissions. NOx emissions show contradictory trends. Some studies report increases of 5-25% (Singh and Paul, 2023; Alawa and Chakma, 2022), while others document reductions of 6-8% (Padhy et al., 2025; Karagoz et al., 2020). Factors increasing NOx: oxygenated compounds increase oxygen availability; higher cetane numbers advance combustion phasing. Factors decreasing NOx: higher water content in bio-oil (3-10 wt%) reduces flame temperature through evaporative cooling; longer ignition delays allow heat dissipation. Karagoz et al. (2020) reported that TPO10D90 reduced NOx by 5-8%. (Table 10).

DOI: 10.60923/issn.2281-4485/24698

Table 9. *Hydrocarbon (HC) emissions at full load for diesel-co-pyrolysis oil blends*

Fuel blend	Engine / conditions	HC (ppm)	Reduction vs. diesel	Reference
D100 (diesel)	Single-cylinder, 1500 rpm, full load	91.5	—	Kumar et al., 2024; Alawa and Chakma, 2022
PO-NC (10% non-catalytic)	Same	67.3	26.4%	Kumar et al., 2024; Alawa and Chakma, 2022
PO-DOL (10% olomite-catalysed)	Same	40.0	56.3%	Kumar et al., 2024; Alawa and Chakma, 2022
PO-SiDOL (10% Si-dolomite)	Same	35.5	61.2%	Kumar et al., 2024; Alawa and Chakma, 2022
PO-ZSM (10% ZSM-5)	Same	51.3	43.9%	Kumar et al., 2024; Alawa and Chakma, 2022
PO-ZSMDOL (10% composite)	Same	58.0	36.6%	Kumar et al., 2024; Alawa and Chakma, 2022
Diesel	Single-cylinder, 1500 rpm, full load	46	—	Senthil et al., 2025
WP (20% wood-plastic co-pyrolysis oil)	Same	32	30.4%	Senthil et al., 2025

Table 10. *Nitrogen oxide (NOx) emission trends with co-pyrolysis oil blends*

Fuel blend	NOx change vs. diesel	Proposed mechanism	Reference
B10 (WCO + PE)	+14% to +25%	Higher combustion temperature, oxygen content	Singh and Paul, 2023
B30 (PP + Calophyllum)	–5.9%	Reduced in-cylinder temperature	Padhy et al., 2025
B10 (LDPE + PP)	+4.7%	Advanced injection timing, higher heat release rate	Alawa and Chakma, 2022
B20 (TPO + diesel)	–8%	Reduced combustion temperature	Karagoz et al., 2020
D90P10 (WCO + PE)	+5% to +12% (depending on injection timing)	Oxygenated fuel, higher peak temperature	Singh and Paul, 2023
TPO10D90 (tire oil)	–5% to –8%	Water content (evaporative cooling), longer ignition delay	Karagoz et al., 2020

Smoke and particulate emissions. Smoke opacity and particulate matter consistently decrease by 5-50% (Padhy et al., 2025; Singh and Paul, 2023; Alawa and Chakma, 2022; Rajamohan and Kasimani, 2018; Karagoz et al., 2020). The primary mechanism is the oxygenated nature of co-pyrolysis oil, which promotes

Table 11. *Smoke opacity at full load for diesel-co-pyrolysis oil blends*

Fuel blend	Engine / conditions	Smoke opacity (%)	Reduction vs. diesel	Reference
Diesel	Single-cylinder, 1500 rpm, full load	28.0	—	Rajamohan and Kasimani, 2018
C10 (10% Calophyllum bio-oil + 2% surfactant)	Same	27.4	2.1%	Rajamohan and Kasimani, 2018
C15 (15% bio-oil)	Same	24.2	13.6%	Rajamohan and Kasimani, 2018
C20 (20% bio-oil)	Same	25.0	10.7%	Rajamohan and Kasimani, 2018
D100 (diesel) at 30° injection timing	Single-cylinder, 1500 rpm, full load	≈40.2	—	Singh and Paul, 2023
D90P10 (10% co-pyrolysis oil) at 30° injection timing)	Same	38.2	5.0%	Singh and Paul, 2023
TPO10D90 (tire oil blend)	Single-cylinder, 1500 rpm, full load	—	5–8% (reduction range)	Karagoz et al., 2020

DOI: 10.60923/issn.2281-4485/24698

soot oxidation. Singh & Paul (2023) observed smoke reductions of 4.9-12.2% for D90P10 across injection timing conditions (Table 11).

Discussion

Environmental benefits

Waste diversion and circular economy. Approximately 40% of plastic waste in India (1.39 million tonnes annually) is landfilled or discarded. Co-pyrolysis offers a pathway to convert this waste into valuable fuel. Alawa and Chakma (2022) estimated that utilising currently landfilled LDPE and PP waste in India could generate 17,188-90,514 billion Btu annually (equivalent to 2.96-15.6 million barrels of oil).

Greenhouse gas emission reduction. Singh and Paul (2023) performed enviroeconomic analysis, finding that co-pyrolysis blends exhibited 1-15% higher CO_2 emission costs than diesel, reflecting more complete combustion rather than increased carbon intensity. The net GHG benefit arises from avoided methane emissions from landfilled waste and displacement of fossil diesel.

Sustainability and exergy analysis. Karagoz et al. (2020) reported that TPO10D90 achieved a sustainability index (SI) of 1.358 vs. 1.337 for diesel at full load, and exergy efficiency of 26.36% vs. 25.19% at 12 Nm load, with 9.5% lower exergy destruction. Singh and Paul (2023) found SI of 1.43 for D90P10 vs. 1.41 for diesel. These results demonstrate that co-pyrolysis oil blends can improve thermodynamic efficiency and sustainability.

Reduction in regulated emissions. Consistent CO reductions (20-40%), HC reductions (20-60%) and smoke reductions (10-50%) directly improve local air quality, especially in urban and agricultural settings where diesel engines are concentrated.

Challenges and limitations

Feedstock variability and preprocessing.Real-world waste streams contain mixed polymers, contaminants and additives. Effective co-pyrolysis requires sorting, cleaning and size reduction, increasing costs.

Bio-oil stability and storage. Co-pyrolysis bio-oil remains susceptible to aging reactions (polymerisation, esterification, acetalisation) that increase viscosity and water content while reducing heating value (Zhang et al., 2007; Oasmaa et al., 2010; Lv et al., 2026).

Engine compatibility and durability. Long-term durability studies are limited. Potential concerns include injector coking, increased wear from acidity, elastomer degradation and deposit formation. Blend ratios of 10-20% are conservative but systematic durability assessments are needed.

NOx trade-off: While some studies report NOx reductions, others document increases of 5-25% (Senthil et al., 2025; Singh & Paul, 2023). NOx mitigation strategies (EGR, injection timing adjustment, SCR) may be required for higher blend ratios.

Catalyst deactivation: Catalytic co-pyrolysis faces coking, sintering and poisoning by feedstock contaminants (Miandad et al., 2016; Hassan et al., 2016; Alawa & Chakma, 2023a).

Economic viability: Singh & Paul (2023) estimated co-pyrolysis oil production cost at ~₹120/L (USD 1.45/L), exceeding diesel prices in India. However, continuous processes and economies of scale would reduce costs, and environmental externalities are not typically included.

Conclusions

This review critically evaluated the environmental benefits of using bio-oil from biomass-plastic co-pyrolysis as a partial diesel substitute in CI engines. The following conclusions are drawn:

Feedstock complementarity. Lignocellulosic biomass (agricultural residues, woody biomass, algae) and waste plastics (especially polyolefins LDPE, HDPE, PP) are complementary. Biomass provides renewable carbon but has high oxygen content (30-50 wt%), while plastics provide high H/C ratios, enabling synergistic hydrogen transfer during co-pyrolysis.

Synergistic mechanisms. Co-pyrolysis operates through radical-driven pathways (hydrogen donation, β-scission, Diels-Alder cycloaddition, hydrocarbon pool) that lower activation energy, suppress oxygenated intermediates and enhance liquid yields beyond additive predictions.

Optimal conditions and oil quality. Conditions of 450-550 °C, biomass:plastic ratios of 1:1 to 3:1, and catalyst incorporation yield bio-oil with improved properties: HHV 34-47 MJ/kg, oxygen content 2.0 - 15.2 wt%, lower acidity and better viscosity. Catalytic co-pyrolysis with ZSM-5, dolomite or metal-modified catalysts further upgrades the oil.

Engine performance. Blends with 10-30 vol% co-pyrolysis oil give BTE of 27-34%, comparable to or exceeding neat diesel, with reduced BSFC for optimised formulations.

DOI: 10.60923/issn.2281-4485/24698

Emission reductions. Significant reductions are achieved: CO 9-40%, HC 20-61%, smoke 5-50%. NOx trends are variable (-6% to +25%) and depend on feedstock, blend ratio and engine conditions.

Environmental benefits. Co-pyrolysis diverts millions of tonnes of waste plastics from landfills, reduces methane generation, displaces fossil diesel, and improves sustainability indices (1.34-1.43) with reduced exergy destruction.

Future research directions should focus on: (1) long-term engine durability studies (500-2000 h), (2) life cycle assessment from feedstock to engine operation, (3) coke-resistant and regenerable catalysts, (4) process intensification for drop-in fuels, (5) real-world mixed waste streams, (6) NOx mitigation strategies specific to co-pyrolysis oil blends, (7) techno-economic analysis at commercial scale, and (8) characterisation of unregulated emissions (PAHs, dioxins, particulate size distribution). In conclusion, biomass-plastic co-pyrolysis bio-oil, when blended with diesel, is a technically viable and environmentally beneficial strategy for reducing pollution from CI engines, mitigating waste management crises and reducing fossil fuel dependence.

Declarations

Funding. Not applicable. This review did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of interest / Competing interests. The author declares no conflict of interest or competing interests.

Ethics approval. Not applicable. This review article does not involve human participants, animal experiments, or any primary data collection requiring ethical approval.

Availability of data and material. Not applicable. This is a review article and does not generate new data. All information presented is cited from publicly available sources.

Authors' contributions. Henok Heluf Gebrekidan is the sole author and contributor to this review article.

Supplementary material. The need for supplementary material is not justified for this review article, as all information is integrated into the main text and references.

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