

Design, Construction and Performance Evaluation of a Low-Cost Pilot-Scale Semi-Batch Pyrolysis Plant for Converting Polystyrene and Low-Density Polyethylene Waste into Fuel Oil

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Abstract

This study reports the design, construction and performance evaluation of a pilot-scale semi-batch pyrolysis plant for converting low-density polyethylene (LDPE) and polystyrene (PS) plastic waste into fuel oil. The plant comprises a 35 kg/batch galvanised steel reactor, an LPG-fired refractory furnace and a counter-current shell-and-tube condenser, all fabricated from locally available materials. Two comparative runs were conducted under non-catalytic, atmospheric conditions using real street-collected waste. Run 1 (PS, 1 kg) achieved an oil yield of 72 wt% and an average oil production rate of 533 mL/h with no solid residue. Run 2 (LDPE, 2.5 kg) achieved an oil yield of 56.9 wt% and 1029 mL/h, with 800 g (32 wt%) of solid residue. The heat source operated at 518–535 °C, while vapour evolution in the reactor headspace began at 150–195 °C (PS) and 175–215 °C (LDPE). The estimated heat duty for LDPE (6088 kJ) was about 2.5 times that of PS (2394 kJ). PS-derived oil had a specific gravity of 0.901–0.903, a flash point of 50 °C, a pour point of 18 °C, a kinematic viscosity of 2.21–2.24 mm²/s, an ash content of 0.07–0.09 wt% and an elevated sulfur content of 3.25–3.42 wt%, attributed to contaminated feedstock. LDPE-derived oil had a specific gravity of 0.790–0.791, a flash point of 50 °C, a pour point of 12 °C, a kinematic viscosity of 2.53–2.58 mm²/s, an ash content of 0.08–0.09 wt% and a sulfur content of 0.18–0.23 wt%. The results demonstrate the technical feasibility of low-cost pilot-scale plastic pyrolysis, report design and heat balance data useful for replication, and identify condenser capacity, reactor material and feedstock pre-treatment as the main targets for improvement.

Highlights

- A 35 kg/batch semi-batch pyrolysis plant was designed and built from locally sourced materials.
- Polystyrene waste gave 72 wt% oil with no solid residue in non-catalytic operation.
- LDPE waste gave 56.9 wt% oil with 32 wt% solid residue and a higher estimated heat duty.
- Both oils met the ASTM D975 viscosity range; flash points fell just below the 52 °C minimum.
- Sulfur of 3.25–3.42 wt% in PS oil shows the cost of using unsorted street-collected feedstock.

1. Introduction

Global plastic production has grown rapidly over recent decades and exceeded 400 million tonnes per year in the early 2020s [1]. Despite recycling initiatives, a large fraction of plastic waste, particularly packaging films and food service containers, is still landfilled or poorly managed, causing soil contamination, microplastic release and greenhouse gas emissions [2, 3]. Low-density polyethylene (LDPE) and polystyrene (PS) form a significant share of municipal solid waste in low- and middle-income countries, where formal recycling infrastructure is limited [4, 5].

LDPE (density 0.910–0.940 g/cm³) is widely used in packaging films, carrier bags and agricultural mulch because of its flexibility and chemical resistance [6]. Its highly branched structure and the contamination typical of post-consumer films limit conventional melt reprocessing, making thermochemical conversion an attractive alternative. PS, produced from styrene monomer, is used extensively in food containers, disposable cups and protective packaging. Its aromatic backbone gives it thermal decomposition behaviour distinct from that of polyolefins, notably a lower degradation onset and a depolymerisation pathway that favours styrene and other aromatics [7, 8].

Pyrolysis, the thermal degradation of polymers at elevated temperature (typically 400–600°C) in the absence of oxygen, is one of the most promising routes for recovering energy and chemicals from plastic waste [9, 10]. The main liquid product consists largely of hydrocarbons in the gasoline and diesel boiling ranges, making it a candidate substitute or blending component for conventional fuels [11]. Unlike incineration, pyrolysis yields a storable liquid product, and unlike mechanical recycling, it tolerates contaminated and mixed polymer streams [12, 13].

LDPE and PS pyrolysis is well documented at laboratory scale [9, 14], and the influence of temperature, heating rate, catalyst and reactor configuration on product distribution and oil quality has been studied extensively [15–17]. However, the translation of these findings into physically constructed pilot systems remains comparatively sparse. Pilot-scale work is essential because it exposes engineering problems that are invisible at gram scale, such as non-uniform heating, condenser limitations, residue removal, insulation losses and feedstock handling, all of which determine whether a technology can be deployed [18–20].

Existing pilot and semi-pilot studies have mostly used fixed-bed batch reactors [21], fluidised-bed systems [22] or rotary kilns [23], and few report purpose-built, low-cost systems intended for resource-constrained settings. Construction methods, material selection rationale and heat balance data for such systems are rarely published, although they are essential for replication and scale-up.

This study addresses that gap by reporting the design, construction and experimental evaluation of a 35 kg/batch semi-batch pyrolysis plant built from locally sourced materials in Nigeria. The specific objectives were:

1. to design and fabricate the reactor, furnace and condenser subsystems;
2. to evaluate the pyrolytic performance of PS and LDPE waste in terms of product yields, temperature profile and estimated heat duty; and
3. to compare the properties of the resulting oils with the ASTM D975 diesel specification and published data.

The central research question was how feedstock chemistry (aromatic PS versus branched aliphatic LDPE) influences product distribution, energy demand and oil quality in a low-cost pilot system operated with real, unsorted waste.

2. Literature Review

Research on plastic pyrolysis has expanded substantially since the early 2010s, driven by environmental pressure and the economics of fuel substitution. A bibliometric review by Armenise et al. [23] identified reactor type, temperature and feedstock composition as the dominant variables governing product distribution. The following subsections summarise the findings most relevant to LDPE and PS and identify the gaps addressed here.

2.1 Reactor design for plastic pyrolysis

Batch and semi-batch reactors dominate pilot-scale plastic pyrolysis because of their simplicity and low capital cost [21]. Fixed-bed batch systems allow good control of feedstock mass and temperature but have limited throughput. Lee et al. [22] showed that fluidised-bed reactors achieve better heat transfer and product uniformity than fixed beds, but their operational complexity and cost restrict adoption in low-resource settings. Continuous reactors offer higher throughput, but long-duration operating data for plastic feedstocks remain scarce [18, 20]. The plant in this study uses a semi-batch configuration, with a fixed feedstock charge and continuous vapour withdrawal, to balance operational simplicity against product recovery.

2.2 Effect of temperature and feedstock on product distribution

Temperature is the most influential parameter governing pyrolysis products. For polyethylene, Aisien and Aisien [24] reported liquid yields maximised in the 450–550°C range, with higher temperatures promoting secondary cracking to gases. González-Aguilar et al. [25] found that expanded PS depolymerises rapidly above about 350°C, with liquid yields above 70 wt% at moderate heating rates. Pan et al. [16] showed that the operating conditions of a semi-batch reactor strongly affect polyethylene conversion and liquid quality, underlining the importance of feedstock preparation and temperature control at larger scale.

Putrawan et al. [21] reported that residue formation in a fixed-bed LDPE reactor increased at lower temperatures, consistent with incomplete cracking of the polyethylene backbone. PS, by contrast, typically leaves negligible residue over a broad temperature range because it depolymerises readily to volatile aromatics [17]. These contrasting behaviours make PS/LDPE co-pyrolysis a complex optimisation problem and motivate the single-feedstock comparison adopted here.

2.3 Fuel oil properties and quality benchmarks

Pyrolysis oils from polyethylene are reported to have specific gravities of roughly 0.78–0.81, consistent with a predominantly aliphatic composition [11, 17]. PS-derived oil contains a high proportion of aromatics, particularly styrene, α -methylstyrene, toluene and ethylbenzene, which raise its density relative to polyethylene oil [7, 17]. Flash points of both oils are commonly reported in the 40–65°C range,

overlapping the ASTM D975 minimum of 52°C, with exact values depending on condensation conditions and retention of light fractions [11].

Sulfur content is a critical quality parameter and a regulatory hurdle for pyrolytic fuels. Oil from pure PS should contain very little sulfur (< 0.1 wt%), since the polymer contains none. Elevated sulfur in waste-derived oils is generally attributed to additives, adhesives, inks and co-mingled packaging materials [3, 7]. This distinction is important for interpreting the oil quality data reported in Section 4.

2.4 Research gaps addressed

Despite a large laboratory-scale literature, three gaps are relevant here: (1) few studies report design specifications and construction methods for low-cost pilot systems; (2) heat balance and condenser design data for PS and LDPE at pilot scale are under-reported; and (3) the effect of real, unsorted street-collected feedstock on oil properties is rarely quantified. This study contributes to all three.

3. Materials and Methods

The work was carried out in three phases: (i) engineering design of the pilot plant; (ii) fabrication and assembly; and (iii) experimental pyrolysis runs with oil characterisation. All experimental work was conducted at the Federal University of Technology Owerri, Nigeria.

3.1 Pilot plant design

3.1.1 Reactor design and material selection

The reactor was designed to process up to 35 kg of plastic waste per semi-batch cycle, a scale suitable for technology demonstration and collection of design data. A vertical cylindrical vessel with a flat welded base and a domed, bolted top end-plate was selected to promote uniform heat transfer while keeping fabrication simple. The internal volume was 52 L, with a diameter of 350 mm and a height of 540 mm, giving a height-to-diameter ratio of about 1.54.

Galvanised steel was selected for the reactor body because of its availability, cost and corrosion resistance during storage. The wall thickness was set at 5 mm, double the theoretical minimum of 2.5 mm calculated from pressure vessel design equations [26], to provide a margin against material degradation. It is acknowledged that the zinc coating of galvanised steel melts at about 420 °C, so the burner-side wall, which is exposed to a 518–535 °C heat source, is likely to lose its coating and may release zinc oxide fume during the first heating cycles. Plain carbon steel or SUS 304 stainless steel is therefore recommended for future builds (Section 4.6). Stainless steel (SUS 304) was used for all vapour-carrying lines and galvanised pipe for the residue removal port. The reactor was designed to operate at atmospheric pressure, which simplifies safety requirements. Reactor specifications are given in Table 1.

Table 1. Reactor design specifications.

Parameter	Value
Internal volume	52 L
Reactor height	540 mm
Reactor diameter	350 mm
Height-to-diameter ratio	1.54
Flange width	25 mm
Feed inlet diameter	75 mm
Wall thickness (actual)	5 mm
Wall thickness (theoretical minimum)	2.5 mm
Bolt size / number (lid flange)	M12 / 9
Bolt size / number (feed inlet)	M12 / 4
Bolt spacing	125 mm
Gasket size / number	50 mm / 2
Vapour outlet pipe diameter	20 mm
Residue outlet pipe diameter	50 mm
Operating pressure	Atmospheric
Design capacity	35 kg/batch

3.1.2 Heating system

An LPG-fired burner was selected as the heat source because of its high calorific value, controllable output and local availability. Burner performance was checked with a water boiling test before installation. The heating system was designed for a nominal heating rate of 20 °C/min. The measured heat source temperature was 518–535 °C. Heat requirements were estimated from the sensible heat needed to bring the charge to its melting point plus the latent heat of vaporisation of each plastic.

3.1.3 Furnace design

The refractory furnace houses the reactor and provides an insulated heating chamber. The furnace shell was 2 mm steel plate, with a 62 mm internal refractory lining cast from bentonite clay (30 kg), sand (35 kg) and water (30 kg), selected for its low thermal conductivity and local availability. Combustion air was supplied by a blower through a 50 mm galvanised pipe. A clearance of 125 mm between the burner and

the reactor base was maintained to distribute heat evenly around the lower reactor wall. Furnace specifications are given in Table 2.

Table 2. Refractory furnace specifications.

Parameter	Value
Total furnace mass	95 kg
Outer shell thickness	2 mm
Refractory lining thickness	62 mm
Bentonite clay content	30 kg
Sand content	35 kg
Water (mix)	30 kg
Burner-to-reactor base clearance	125 mm
Air supply pipe diameter	50 mm
Air supply pipe length (blower to furnace)	1 m
Combustion chamber height and width	500 mm

3.1.4 Condenser design

A single-tube, counter-current shell-and-tube condenser was designed to condense the pyrolysis vapours. A SUS 304 stainless steel tube ($\frac{3}{4}$ -inch, 20 mm OD) with an effective length of 914.4 mm was housed in a 1-inch (25 mm) polymeric shell. The condenser was inclined slightly downward towards the collection flask to allow gravity drainage. Chilled water, supplemented with ice blocks, was used as the shell-side coolant. Stainless steel was chosen for the tube for its resistance to hydrocarbon vapours and acidic by-products. Condenser specifications are given in Tables 3 and 4.

Table 3. Condenser component specifications.

Component	Specification
Connecting V-pipe	2-inch
Shell pipe	1-inch (25 mm), polymeric
Vapour-side tube	$\frac{3}{4}$ -inch (20 mm), SUS 304 stainless steel
Shell end covers	1-inch ($\times 2$)
Water inlet/outlet ports	$\frac{1}{2}$ -inch (12.5 mm)
Hose connections	$\frac{3}{4}$ -inch
2-inch bend fitting	18.7 mm radius
Tube socket fittings	$\frac{3}{4}$ -inch socket

Table 4. Condenser performance specifications.

Parameter	Value
Condenser type	Shell-and-tube
Flow arrangement	Counter-current
Shell-side fluid	Chilled water
Tube-side fluid	Pyrolysis vapour
Tube OD	20 mm ($\frac{3}{4}$ -inch)
Shell ID	25 mm (1-inch)
Effective tube length	914.4 mm
Number of tubes / passes	1 / 1

3.1.5 Reactor stand

A stand fabricated from 2-inch angle iron, measuring 520 × 520 × 520 mm and fitted with 50 mm roller wheels, supports the reactor centrally within the furnace chamber and allows the assembly to be repositioned.

3.1.6 Process flow

The process flow is shown in Figure 1. Shredded plastic is charged through the top inlet, and the reactor is sealed with bolted flanges to exclude air. As the furnace heats the reactor, the plastic melts and decomposes, and the vapours travel through the 20 mm stainless steel line to the condenser, where they

are condensed and collected in a graduated flask. Non-condensable gases leave the end of the condenser and are vented to a flare. After each run the reactor is cooled, the solid residue is removed through the 50 mm port, and the oil volume and mass are recorded.

3.2 Plant construction

3.2.1 Reactor fabrication

The reactor body was rolled from 5 mm galvanised steel sheet and seam-welded longitudinally. A flat plate was welded to the base, and a domed top end-plate was attached to the body through a flange ring secured by nine M12 bolts. A hydrostatic test (water-filled, with visual inspection) was used to verify weld integrity, and leaks were rectified by additional welding. Two openings were made in the top: a 75 mm feed inlet with a bolted flange and a 20 mm vapour outlet, to which the vapour pipe was socket-welded. Figure 2 shows the completed reactor, and Figure 3 shows a top view of the assembly.

3.2.2 Thermal insulation

To reduce heat loss and LPG consumption, the reactor was placed concentrically inside a slightly larger cylindrical shell, and the annular gap was packed with a sand–sawdust mixture as low-cost insulation. The top annulus was sealed with a mixture of sawdust, sand and cement.

3.2.3 Sealing of the reactor

The lid flange (nine M12 bolts at 125 mm spacing) and the feed inlet flange (four M12 bolts) were fitted with gaskets to keep air out during operation and ensure that the charge underwent pyrolysis rather than oxidation. Seal integrity was checked with a pressurised nitrogen test before the experimental runs. The reactor headspace was not purged with nitrogen before heating, so a small amount of residual air was present at start-up.

3.2.4 Refractory furnace fabrication

The furnace lining was cast in situ around the reactor footprint. Bentonite clay, sand and water were mixed to a workable consistency and cast to a wall thickness of 62 mm. The lining was cured at ambient temperature for 72 h and then fired slowly to remove residual moisture and prevent cracking.

3.2.5 Condenser fabrication

The condenser shell was fabricated from a standard plastic dispenser tank with two coaxial ports bored in opposite faces. The stainless steel tube was passed through both ports and sealed with socket

fittings, and water inlet and outlet connections were fitted through the shell wall. The condenser was tested with cold water flow and a steam source before integration into the plant.

3.3 Experimental procedure

3.3.1 Feedstock collection and preparation

Plastic waste was collected from municipal solid waste streams in Owerri, Nigeria. The PS feedstock consisted of used food containers, disposable cups and packaging foam, and the LDPE feedstock of carrier bags and agricultural film. Both were sorted to remove gross contaminants (metal and glass) and shredded to a particle size of about 20 mm. The feedstocks were not washed or chemically purified, so they represent real street waste that may contain adhesive residues, printing inks and laminate layers. This is relevant to the sulfur results discussed in Section 4.4.

3.3.2 Operating protocol

A semi-batch protocol was used, combining a fixed feedstock charge with continuous vapour withdrawal and condensation:

- i. the reactor was charged with shredded feedstock and sealed;
- ii. the burner was ignited and set to maximum LPG output;
- iii. the onset of condensate flow at the condenser outlet was recorded;
- iv. oil was collected continuously in the graduated flask;
- v. the run was ended when no further condensate was observed for 10 min; and
- vi. the reactor was cooled and opened, and the solid residue was collected and weighed.

3.3.3 Run conditions

Run 1 used 1 kg of PS and Run 2 used 2.5 kg of LDPE. Both runs were conducted at atmospheric pressure with the burner at maximum output (heat source temperature 518 °C for Run 1 and 535 °C for Run 2). Temperatures were measured by thermocouples in the reactor headspace and at the condenser vapour inlet and outlet and cooling water inlet and outlet. Run 1 lasted 1.5 h and Run 2 lasted 1.75 h. Each feedstock was tested in a single run, so the results are comparative rather than statistical; replication is identified as a priority for future work (Section 5).

3.4 Oil characterisation

The oils were characterised as follows:

- i. *Specific gravity*: determined at ambient temperature with a 50 mL pycnometer as $SG = (m_{oil} - m_{empty}) / (m_{water} - m_{empty})$.
- ii. *Flash point*: Pensky-Martens closed cup method (ASTM D93), with the test flame applied at 1 °C intervals; the mean of three determinations is reported.
- iii. *Cloud and pour point*: ASTM D2500 and ASTM D97, by controlled cooling of the sample in a jacketed test jar and observation at 3 °C intervals.
- iv. *Kinematic viscosity*: ASTM D445 at 40 °C using a calibrated glass capillary viscometer in a thermostatic bath.
- v. *Ash content*: a weighed sample was ignited in a muffle furnace at 600 °C to constant mass, following the principle of ASTM D482.
- vi. *Sulfur content*: energy-dispersive X-ray fluorescence (ASTM D4294).

4. Results and Discussion

4.1 Pilot plant overview

The completed plant comprises four integrated subsystems: the insulated reactor, the refractory LPG furnace, the shell-and-tube condenser and the product collection system (Figure 4). The plant is designed for 35 kg per batch and operates on a semi-batch cycle.

4.2 Product yields

Table 5 presents the mass balance for both runs. Run 1 (PS, 1 kg) produced 800 mL of oil with no solid residue, and Run 2 (LDPE, 2.5 kg) produced 1800 mL of oil and 800 g of solid residue. The larger oil volume from LDPE reflects the larger charge; on a mass basis, PS gave the higher oil yield (72.0 versus 56.9 wt%). The absence of residue in the PS run is consistent with its depolymerisation to volatile monomer and oligomers [7,25]. LDPE degrades by random scission of long aliphatic chains, which is more prone to incomplete conversion when part of the charge remains only slightly above its degradation onset, leaving heavy waxy and carbonaceous residue [16,21].

Table 5. Mass balance and performance metrics for Run 1 (PS) and Run 2 (LDPE).

Parameter	Run 1 (PS)	Run 2 (LDPE)
Feedstock mass (g)	1000	2500
Operation time (h)	1.50	1.75
Volume of oil collected (mL)	800	1800
Mass of oil (g)	720	1422
Mass of solid residue (g)	Nil	800
Gas and losses (g) ^a	280	278
Oil yield (wt%)	72.0	56.9
Gas and losses (wt%)	28.0	11.1
Solid residue (wt%)	0.0	32.0
Average oil production rate (mL/h)	533	1029

^a Calculated by difference: feedstock mass – oil mass – residue mass. This value includes non-condensable gas and any uncondensed vapour, aerosol or handling losses.

Oil mass calculated from the collected volume and the measured specific gravity of each oil (0.902 for PS and 0.790 for LDPE).

The gas-and-loss fraction was much higher for PS (28 wt%) than for LDPE (11.1 wt%). Styrene, the main PS product, boils at about 145 °C and should condense at the measured condenser outlet temperature of 65 °C, so the difference is more plausibly explained by the limited capacity of the short single-tube condenser at the vapour release rates of PS, which depolymerises rapidly once its onset temperature is reached. Rapid vapour release shortens residence time in the condenser, and part of the condensable fraction can leave as vapour or aerosol, together with genuinely light gases [25]. Because the gas fraction was determined by difference and not measured, these values also absorb experimental losses. A larger or two-stage condenser, possibly with a demister, is expected to raise the oil yield from PS.

4.3 Temperature profile and heat duty

The temperature profiles of both runs are summarised in Table 6. Vapour evolution, defined as the onset of condensate flow, began at headspace temperatures of 150 °C (PS) and 175 °C (LDPE) and continued up to 195 °C and 215 °C, respectively. These values are lower than typical pyrolysis temperatures (400–550 °C) because they were measured in the vapour space above the charge, which is cooled by the escaping vapour, and not at the burner-side wall or within the melt, which are substantially hotter. The thermocouple arrangement did not allow direct measurement of the wall or melt temperature, and this is recommended for future work. Based on the times to first vapour, the average headspace heating rates

were about 3.9 °C/min (PS) and 3.2 °C/min (LDPE), well below the nominal design rate of 20 °C/min, reflecting heat losses and the thermal mass of the reactor and furnace.

Table 6. Temperature profile summary for Run 1 (PS) and Run 2 (LDPE).

Parameter	Run 1 (PS)	Run 2 (LDPE)
Ambient temperature (°C)	32	32
Heat source temperature (°C)	518	535
First melt observed (°C)	118	135
Vapour onset temperature (°C)	150	175
Peak vapour temperature (°C)	195	215
Condenser vapour inlet (°C)	173	195
Condenser outlet (°C)	65	95
Cooling water inlet (°C)	0	25
Cooling water outlet (°C)	25	45
Time to first vapour (min)	~30	~45

The higher melt and vapour onset temperatures of LDPE reflect its greater thermal stability, since breaking its long aliphatic chains requires more energy than unzipping the PS backbone. This is consistent with the heat analysis in Table 7, where the estimated heat duty for LDPE (6088 kJ) was about 2.5 times that of PS (2394 kJ). The estimated heat duty was calculated as the heat transfer rate multiplied by the run time; it therefore represents the heat that must be removed by the condenser and is an indicator of, not a direct measurement of, the energy supplied by the burner.

The cooling water flow rates in Table 7 were not measured directly but were calculated from the heat balance as $m_w = Q / (c_{p,w} \Delta T_w)$, where Q is the heat transfer rate (kJ/h), $c_{p,w}$ is the specific heat capacity of water (4.187 kJ/kg·°C) and ΔT_w is the cooling water temperature rise (25 °C for PS and 20 °C for LDPE). The resulting values of 15.2 kg/h (PS) and 41.4 kg/h (LDPE) are the minimum supply required for full condensation under the recorded conditions and provide a baseline for condenser sizing. The log mean temperature difference was calculated for counter-current flow from the terminal temperatures in Table 6.

Table 7. Heat analysis for Run 1 (PS) and Run 2 (LDPE).

Parameter	Run 1 (PS)	Run 2 (LDPE)
Estimated heat duty (kJ)	2394	6088
Heat transfer rate (kJ/h)	1596	3479
Cooling water flow rate, calculated (kg/h)	15.2	41.4
Log mean temperature difference (°C)	100.9	105.0
Latent heat of vaporisation assumed (kJ/kg) ^a	180.5	180.5
Average volatile release rate (kg/h) ^b	0.67	0.97

^a A single representative value was assumed for both polymers in the absence of polymer-specific data.

^b (Feedstock mass – residue mass)/run time.

LDPE required a cooling water flow more than twice that of PS, with direct implications for water and energy use at scale. Together with the high gas-and-loss fraction from PS, this identifies the condenser as the main constraint of the present design.

4.4 Fuel oil properties

Table 8 compares the measured properties of the PS- and LDPE-derived oils with the ASTM D975 Grade No. 2-D diesel specification and typical values for comparable pyrolysis oils [7,11,17,24].

Table 8. Properties of PS-derived oil, LDPE-derived oil, No. 2-D diesel and literature pyrolysis oils.

Property	PS oil (this study)	LDPE oil (this study)	No. 2-D diesel ^a	PS oil (literature) [7,17]	PE oil (literature) [11,24]
Specific gravity	0.901–0.903	0.790–0.791	0.820–0.845 ^b	0.880–0.920	0.780–0.810
Flash point (°C)	50	50	≥52	42–60	38–58
Pour point (°C)	18	12	–6 to –15 ^b	15–25	9–18
Kinematic viscosity at 40 °C (mm ² /s)	2.21–2.24	2.53–2.58	1.9–4.1	1.9–2.8	2.1–3.2
Ash (wt%)	0.07–0.09	0.08–0.09	≤0.01	0.05–0.12	0.04–0.10
Sulfur (wt%)	3.25–3.42	0.18–0.23	≤0.0015 ^c	<0.1 ^d	0.05–0.30

^a ASTM D975 Grade No. 2-D. ^b Typical commercial values; not specified in ASTM D975. ^c S15 grade. ^d Value for oil from clean PS; the elevated value in this study is attributed to feedstock contamination (see text).

The specific gravity of the LDPE-derived oil (0.790–0.791) is slightly below the typical range for commercial diesel (0.820–0.845) and within the range reported for polyethylene pyrolysis oils, indicating a predominantly aliphatic composition with a significant light fraction. The higher specific gravity of the PS-derived oil (0.901–0.903) reflects its aromatic content, since aromatics are denser than aliphatic hydrocarbons of similar carbon number [7].

Both oils had a flash point of 50 °C, just below the ASTM D975 minimum of 52 °C. This is common for pyrolysis oils and reflects the presence of light volatile components [11]. Removal of the lightest fraction by a mild distillation cut would be expected to bring the flash point within specification.

The pour points of 18 °C (PS oil) and 12 °C (LDPE oil) are well above those of commercial diesel and would limit use in cold climates. In tropical regions such as southern Nigeria, where ambient temperatures rarely fall below these values, cold-flow behaviour is unlikely to restrict use.

The kinematic viscosities of 2.21–2.24 mm²/s (PS oil) and 2.53–2.58 mm²/s (LDPE oil) at 40 °C fall within the ASTM D975 range of 1.9–4.1 mm²/s, suggesting compatibility with diesel injection systems from a viscosity standpoint.

The sulfur content of the LDPE-derived oil (0.18–0.23 wt%) is far above that of ultra-low-sulfur diesel (≤ 0.0015 wt%) but within the range reported for oils from post-consumer polyethylene. Sulfur in polyethylene-derived oil typically originates from additives such as sulfur-containing antioxidants, and from co-mingled waste [3]. The sulfur content of the PS-derived oil (3.25–3.42 wt%) was markedly higher and anomalous for PS, which contains no sulfur. It is attributed to the unwashed street-collected feedstock, which contained adhesive labels, laminate films and printing inks, all potential sources of organic sulfur. Because the feedstock itself was not analysed for sulfur, this attribution should be confirmed in future work by testing clean PS under identical conditions. The finding nevertheless shows that feedstock sorting and washing, or downstream desulfurisation, would be required before PS-derived oil from such waste could be used as a fuel [7].

Ash content was low for both oils (0.07–0.09 wt%), consistent with the low inorganic content of the condensed products, although it remains above the ASTM D975 limit of 0.01 wt%.

4.5 Comparison of PS and LDPE

The two feedstocks showed distinct performance profiles that reflect their polymer chemistry. PS gave the higher oil yield (72 wt%) at a lower estimated heat duty and left no solid residue, which simplifies operation by eliminating residue handling. However, its high gas-and-loss fraction (28 wt%) represents

material that could probably be recovered with better condensation, and its oil quality was compromised by feedstock sulfur.

LDPE gave a lower oil yield (56.9 wt%) and a higher average production rate in mL/h, mainly because a 2.5 times larger charge was processed. Its oil had much lower sulfur (0.18–0.23 wt%) and is more amenable to fuel use after basic upgrading. The large solid residue fraction (32 wt%) is an operational drawback, since it must be removed between batches, and its magnitude suggests that part of the charge did not reach full decomposition temperature. Pyrolysis residues from polyethylene have been investigated as fillers and carbon precursors, offering a possible secondary use [14].

For mixed municipal waste containing both polymers, these results suggest that sorting by polymer type would allow operation to be tailored to each feedstock: shorter, lower-energy cycles for PS and greater cooling capacity and longer holding times for LDPE. Co-pyrolysis of PS/LDPE blends is a logical next step, since interactions between the aromatic and aliphatic radicals may improve LDPE conversion and reduce residue [7,13].

4.6 Limitations

The results should be interpreted in light of several limitations. First, each feedstock was tested in a single run, at charges (1 and 2.5 kg) well below the 35 kg design capacity, so the data are comparative and do not support statistical inference or confirm performance at full load. Second, gas yields were obtained by difference, and the gas was not analysed. Third, temperatures were measured in the reactor headspace only, so the wall and melt temperatures that govern decomposition are unknown. Fourth, the oils were not analysed for composition (for example by GC-MS) or calorific value. Fifth, the galvanised steel reactor is unsuitable for long-term operation above about 420 °C because of zinc coating loss and potential zinc oxide fume; carbon steel or stainless steel should be used in future builds. Finally, the reactor was not purged with nitrogen before heating, so limited oxidation of the charge at start-up cannot be excluded.

5. Conclusions

A 35 kg/batch semi-batch pyrolysis plant was designed, built from locally available materials and operated with real street-collected PS and LDPE waste. The main conclusions are:

1. The plant was successfully constructed and operated, demonstrating the technical feasibility of low-cost, locally fabricated pyrolysis systems for plastic waste valorisation in resource-constrained settings.
2. PS gave an oil yield of 72 wt% with no solid residue and an estimated heat duty of 2394 kJ. LDPE gave 56.9 wt% oil and 32 wt% residue with an estimated heat duty of 6088 kJ, reflecting the greater thermal stability of polyethylene.

- Both oils had kinematic viscosities ($2.21\text{--}2.58\text{ mm}^2/\text{s}$ at 40°C) within the ASTM D975 range and flash points (50°C) just below the 52°C minimum, indicating potential as diesel blending components after light-end removal and further upgrading.
- The high sulfur content of the PS-derived oil ($3.25\text{--}3.42\text{ wt}\%$) is attributed to contamination of the unwashed feedstock and highlights the importance of feedstock sorting and pre-treatment.
- The high calculated cooling water demand for LDPE and the large gas-and-loss fraction for PS identify the condenser as the main target for improvement, together with replacement of galvanised steel in the reactor.

Recommendations for future work

- Replicate runs (at least in triplicate) for each feedstock, including runs at or near the 35 kg design capacity.
- Multi-point temperature measurement at the reactor wall, within the melt and in the headspace, with measurement of LPG consumption to close the energy balance.
- GC-MS, calorific value and distillation analysis of the oils, and composition analysis of the non-condensable gas.
- Comparison of washed and unwashed PS, with sulfur analysis of the feedstock, to quantify the contribution of contamination.
- Co-pyrolysis of PS/LDPE blends to assess effects on oil yield and residue formation.
- An enlarged or two-stage condenser and a carbon steel or stainless steel reactor.
- Life cycle assessment and techno-economic analysis relative to landfilling and incineration.

Declarations

Author contributions (CRediT): M.V.A.: Conceptualisation, Methodology, Formal analysis, Writing – original draft, Writing – review and editing. E.D.E.: Investigation, Plant construction, Data collection, Resources, Writing – original draft. B.C.N.: Formal analysis, Writing – review and editing. M.A.T.: Investigation, Plant construction. A.P.O.: Resources, Investigation. M.D.A.: Investigation, Data curation. S.T.T.: Investigation, Methodology support. All authors read and approved the final manuscript.

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References

1. Pilapitiya PGCNT, Ratnayake AS (2024) The world of plastic waste: A review. *Clean Mater* 11:100220
2. Kibria MG, Masuk NI, Safayet R, Nguyen HQ, Mourshed M (2023) Plastic waste: Challenges and opportunities to mitigate pollution and effective management. *Int J Environ Res* 17:20
3. Hahladakis JN, Velis CA, Weber R, Iacovidou E, Purnell P (2018) An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. *J Hazard Mater* 344:179–199
4. Kehinde O, Ramonu OJ, Babaremu KO, Justin LD (2020) Plastic wastes: Environmental hazard and instrument for wealth creation in Nigeria. *Heliyon* 6, e05131
5. Kumar R, Verma A, Shome A et al (2021) Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. *Sustainability* 13:9963
6. Poh L, Wu Q, Chen Y, Narimissa E (2022) Characterization of industrial low-density polyethylene: A thermal, dynamic mechanical, and rheological investigation. *Rheol Acta* 61:701–720
7. Jahirul MI, Rasul MG, Schaller D, Khan MMK, Hasan MM, Hazrat MA (2022) Transport fuel from waste plastics pyrolysis: A review on technologies, challenges and opportunities. *Energy Conv Manag* 258:115451
8. Seewoo BJ, Wong EVS et al (2024) Impacts associated with the plastic polymers polycarbonate, polystyrene, polyvinyl chloride, and polybutadiene across their life cycle: A review. *Heliyon* 10, e32912
9. Qureshi MS, Oasmaa A, Pihkola H et al (2020) Pyrolysis of plastic waste: Opportunities and challenges. *J Anal Appl Pyrol* 152:104804
10. Kabeyi MJB, Olanrewaju OA (2023) Review and design overview of plastic waste-to-pyrolysis oil conversion with implications on the energy transition. *Journal of Energy* 2023, 1–25
11. Anuar Sharuddin SD, Abnisa F, Daud W, Aroua WMA, M.K (2017) Energy recovery from pyrolysis of plastic waste: Study on non-recycled plastics (NRP) data as the real measure of plastic waste. *Energy Conv Manag* 148:925–934
12. Abdy C, Zhang Y, Wang J, Yang Y, Artamendi I, Allen B (2022) Pyrolysis of polyolefin plastic waste and potential applications in asphalt road construction: A technical review. *Resources, Conservation and Recycling* 180, 106213
13. Al-Rumaihi A, Shahbaz M, McKay G, Mackey H, Al-Ansari T (2022) A review of pyrolysis technologies and feedstock: A blending approach for plastic and biomass towards optimum biochar yield. *Renew Sustain Energy Rev* 167:112715
14. Sogancioglu M, Yel E, Ahmetli G (2017) Pyrolysis of waste high density polyethylene (HDPE) and low density polyethylene (LDPE) plastics and production of epoxy composites with their pyrolysis chars. *J Clean Prod* 165:369–381

15. Anuar Sharuddin SD, Abnisa F, Daud W, Aroua WMA, M.K (2016) A review on pyrolysis of plastic wastes. *Energy Conv Manag* 115:308–326
16. Pan R, Ferreira Martins M, Debenest G (2021) Pyrolysis of waste polyethylene in a semi-batch reactor to produce liquid fuel: Optimization of operating conditions. *Energy Conv Manag* 237:114114
17. Miandad R, Barakat MA, Aburiazaiza AS, Rehan M, Ismail IMI, Nizami AS (2017) Effect of plastic waste types on pyrolysis liquid oil. *Int Biodeterior Biodegrad* 119:239–252
18. Singh A, Singh DK, Ojha DK (2024) Chemical engineering perspective of pyrolysis reactor and condenser system for biomass valorisation. *Sustainable Chem Clim Action* 5:100046
19. Faisal F, Rasul MG, Jahirul MI, Schaller D (2023) Pyrolytic conversion of waste plastics to energy products: A review on yields, properties, and production costs. *Sci Total Environ* 861:160721
20. Kulas DG, Zolghadr A, Shonnard DR (2022) Liquid-fed waste plastic pyrolysis pilot plant: Effect of reactor volume on product yields. *J Anal Appl Pyrol* 166:105601
21. Putrawan IMA, Suarbawa IKGJ, Rajendra IM, Winaya I (2021) Design and fabrication of a fixed bed pyrolysis with LDPE plastic waste. *LOGIC: Jurnal Rancang Bangun dan Teknologi* 21:179–183
22. Lee M, Ko H, Oh S (2023) Pyrolysis of solid recovered fuel using fixed and fluidized bed reactors. *Molecules* 28:7815
23. Armenise S, SyieLuing W, Ramírez-Velásquez JM et al (2021) Plastic waste recycling via pyrolysis: A bibliometric survey and literature review. *J Anal Appl Pyrol* 158:105265
24. Aisien FA, Aisien ET (2023) Production and characterization of liquid oil from the pyrolysis of waste high-density polyethylene plastics using spent fluid catalytic cracking catalyst. *Sustainable Chem Clim Action* 2:100020
25. González-Aguilar AM, Cabrera-Madera VP, Vera-Rozo JR, Riesco-Ávila JM (2022) Effects of heating rate and temperature on the thermal pyrolysis of expanded polystyrene post-industrial waste. *Polymers* 14:4957
26. Moss DR, Basic M (2013) *Pressure Vessel Design Manual*, 4th edn. Butterworth-Heinemann, Oxford

Figures

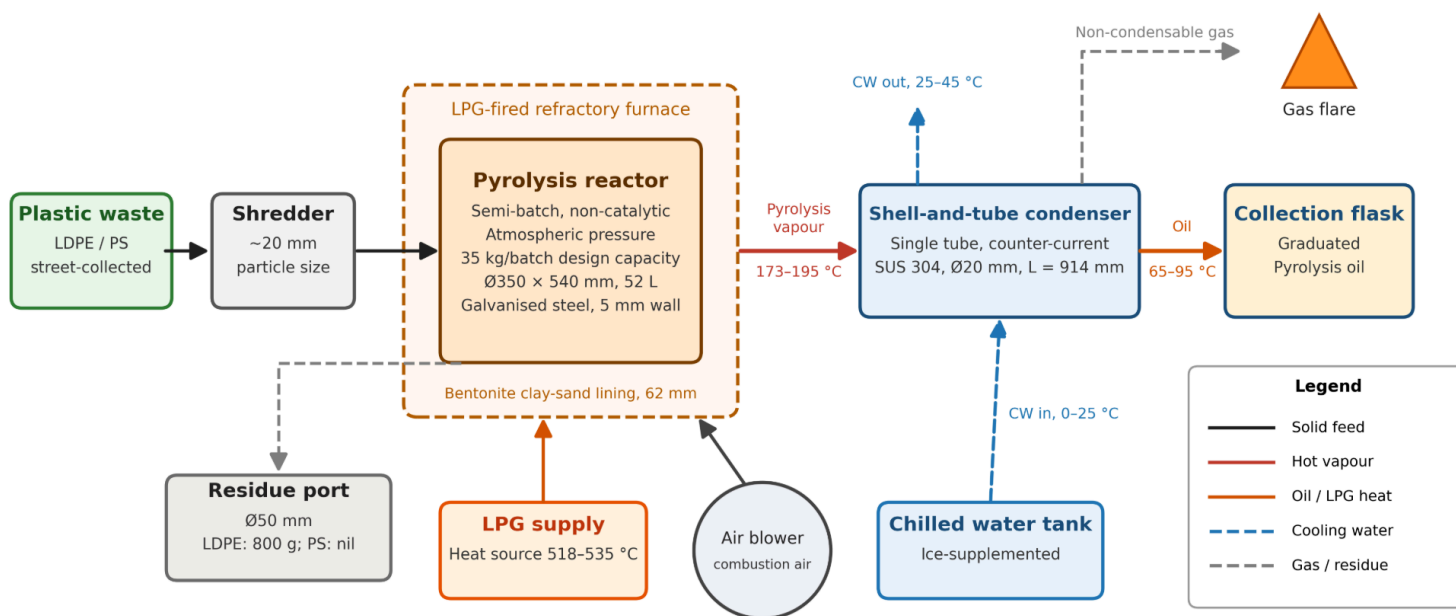


Figure 1

Process flow diagram of the pilot-scale semi-batch pyrolysis plant.



Figure 2

Fabricated pyrolysis reactor showing the cylindrical body, domed top end-plate, bolted flange ring and vapour outlet stub (side view).



Figure 3

Top view of the reactor assembly showing the vapour outlet stub, bolted flange ring, air supply pipe (Ø50 mm) and outer steel furnace casing.

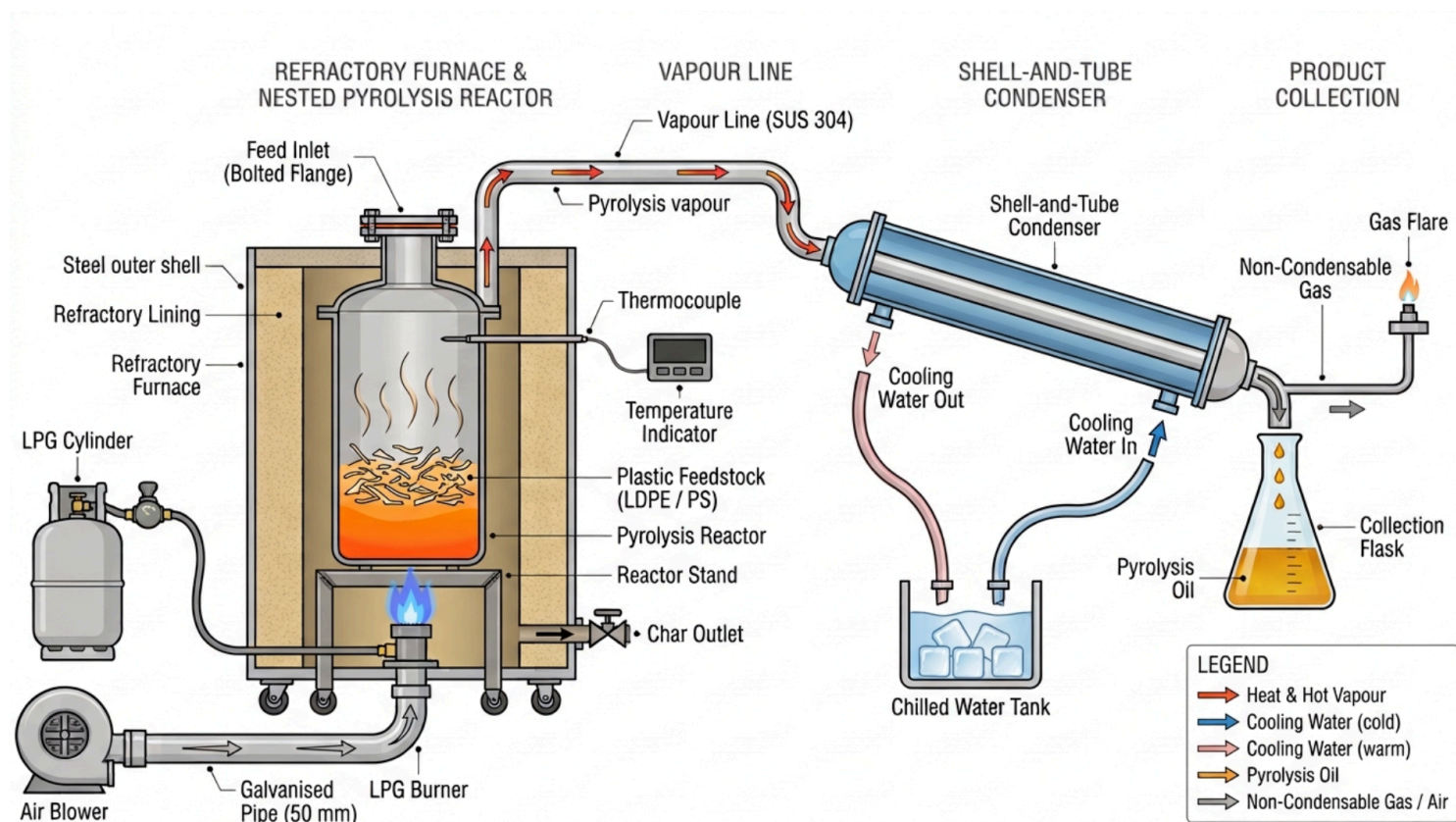


Figure 4

Schematic of the pilot-scale semi-batch pyrolysis plant as constructed and operated.

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