Decentralized Fractional Pyrolysis of Polyolefin Waste Using Passive Air-Cooled Condensers: A Zero-Electricity, Low-Capital System Developed at Mulungushi University, Zambia

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ABSTRACT

The escalating accumulation of plastic waste presents a severe environmental challenge across Zambia, where municipal waste management infrastructure remains limited and recycling rates are critically low. This article presents a novel, low-cost apparatus and method for the pyrolytic conversion of plastic waste, specifically High-Density Polyethylene (HDPE) and Low-Density Polyethylene (LDPE), into separated liquid hydrocarbon fuels. The system was designed, constructed, and experimentally validated at Mulungushi University in Kabwe, Zambia, using only locally available materials including reclaimed steel drums, clay soil, and metal pipe. The apparatus comprises a sealable metal drum reactor heated by an external biomass furnace, a unique mud-based air-tight seal, and a series of at least three passively air-cooled condensers. Unlike conventional pyrolysis systems requiring active temperature control, catalysts, or grid electricity, this design establishes a natural thermal gradient across the condenser series, effecting fractional condensation without any moving parts or external energy inputs. Ten experimental runs conducted at Mulungushi University demonstrated that the first condenser yields a petrol-diesel mixture, while subsequent condensers produce petrol-rich fractions. The average total liquid yield was 10.2 kg from 15 kg of HDPE feedstock, representing a mass conversion efficiency of 68%. A comprehensive energy balance revealed an overall thermal efficiency of 73%. Fuel property analysis confirmed that the fractions exhibit properties comparable to commercial petrol and diesel, with density ranging from 680 to 810 kg/m³ and gross calorific values between 44.8 and 45.5 MJ/kg. This apparatus offers a scalable, decentralized solution for Zambian communities, small-scale entrepreneurs, and rural institutions to transform waste plastic into usable fuel, simultaneously addressing urban plastic pollution and energy poverty. The technology is constructed entirely from materials available in any Zambian town or village and operates using waste biomass such as maize stalks, groundnut shells, or scrap wood. Preliminary economic analysis indicates a payback period of 4-6 months for small-scale operation, suggesting viable commercial potential.

Keywords: Pyrolysis, plastic waste, fractional condensation, HDPE, LDPE, biomass heating, low-cost technology, Zambia, Mulungushi University, circular economy, appropriate technology.

INTRODUCTION

The Plastic Waste Challenge in Zambia

Zambia, like many sub-Saharan African nations, faces a rapidly growing plastic waste crisis. According to the Zambia Environmental Management Agency (ZEMA), the country generates approximately 85,000 tonnes of

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plastic waste annually, with only an estimated 10 to 15 percent collected for recycling (ZEMA, 2022). The remainder accumulates in uncontrolled dumpsites, roadside drains, waterways, and natural environments across Lusaka, the Copperbelt, and other urban centers. In particular, the Kafue River and the Lusaka city drainage system have become choked with discarded plastic packaging, much of which is HDPE from milk bottles, cooking oil containers, and household chemical packaging.

Current waste management practices in Zambia are inadequate to address this challenge. Open dumping at sites such as the Chunga landfill in Lusaka remains the primary disposal method, with minimal environmental controls. While the Chunga landfill is the primary designated site, it faces capacity constraints, and new efforts involve re-engineering it with modern cells using the Fukuoka Method, a low-cost, semi-aerobic landfill technique introduced through international cooperation. Only about 45% of waste is formally collected in Zambia, leaving significant room for infrastructure growth. Open burning of plastic waste is common in peri-urban and rural areas, releasing toxic emissions including dioxins, furans, and particulate matter that contribute to respiratory diseases and environmental contamination. The informal recycling sector, while active, primarily focuses on higher-value plastics such as clear PET bottles, leaving HDPE and other polyolefins largely unmanaged (Chanda & Banda, 2021).

The regulatory framework, under the Solid Waste Regulation and Management Act No. 20 of 2018 and the Environmental Management Act No. 12 of 2011, establishes the principle of Extended Producer Responsibility (EPR), which legally mandates manufacturers to manage the end-of-life cycle of their packaging and products (ZEMA, 2018). However, enforcement of EPR regulations has proven challenging in practice. Research on Zambia's EPR implementation has found that there is no effective enforcement or accountability for non-compliant players, with only large incumbents typically obeying the requirements while technically banned bags remain widely used. The responsible entity, ZEMA, does not have personnel deployed across the entire country, limiting its capacity to enforce the instrument effectively.

Mulungushi University's Role in appropriate technology development

Mulungushi University, located in Kabwe approximately 140 kilometers north of Lusaka, has established a research focus on appropriate and sustainable technologies for Zambian conditions. The university's Directorate of Research and Innovation and Office of the Resident Engineer has prioritized the development of low-cost solutions that can be implemented using locally available materials and skills, bypassing the need for imported equipment or specialized infrastructure. This institutional commitment aligns with broader sustainable development goals and the recognition that technology transfer models based on imported equipment often fail in resource-limited contexts (Mulungushi University, 2022). The present work emerged from this mandate, seeking to address the dual problems of plastic waste accumulation and household energy poverty through a single integrated technology.

Pyrolysis as a Solution: A Review of Existing Technologies

Pyrolysis, the thermal decomposition of organic materials in an oxygen-deprived environment, offers a scientifically established pathway to convert waste plastics back into hydrocarbon oils and gases (Sharuddin et al., 2016). The process involves heating plastic waste to temperatures typically between 350°C and 600°C in the absence of oxygen, causing the long polymer chains to crack into shorter hydrocarbon molecules that can be condensed into liquid fuels.

Geyer et al. (2017) estimated that approximately 6,300 million tonnes of plastic waste had been generated globally by 2015, of which only 9% had been recycled, 12% incinerated, and 79% accumulated in landfills or the natural environment. This staggering figure underscores the urgent need for effective plastic waste management technologies, particularly in developing countries where waste management infrastructure is limited.

Numerous studies have investigated the pyrolysis of plastic waste, focusing on various feedstocks including HDPE, LDPE, polypropylene (PP), and polystyrene (PS). Kumar and Singh (2011) reported liquid yields of

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up to 77.0% (v/w) from HDPE pyrolysis, with the oil exhibiting properties similar to commercial diesel. A comprehensive review by Wong et al. (2015) examined the current state and future prospects of plastic waste pyrolysis, identifying key challenges including the high cost of conventional systems, the need for effective catalysis, and the economic viability of the process.

However, existing pyrolysis technologies that demonstrate commercial viability typically require electrically heated reactors, water-cooled condensation systems, catalytic cracking beds, or sophisticated distillation columns (Sharuddin et al., 2016). Industrial systems utilize continuous screw or fluidized bed reactors with computerized temperature control, refrigerated or water tower cooling, and advanced fractionation. For example, patent EP3894516B1 describes a system operating at 450-500°C with heat exchangers, gas-liquid separators, and water-cooling systems, demonstrating the complexity of conventional approaches. These requirements make conventional systems economically unviable and operationally impractical for deployment in Zambian rural areas, peri-urban settlements, or even small-scale municipal operations.

Research on pyrolysis has been particularly limited in developing countries due to a lack of equipment for research and the high cost of imported reactors (Ibitoye et al., 2025). A low-cost, laboratory-scale, locally fabricated, and open-access pyrolysis reactor remains understudied and scarce in these contexts, creating a structural barrier to pyrolysis adoption where it is needed most. Recent efforts have demonstrated the feasibility of indigenous reactor construction using local materials, with total construction costs as low as USD 557 for laboratory-scale biomass pyrolysis reactors (Ibitoye et al., 2025). Similarly, portable, low-cost pyrolysis reactors have been designed and constructed specifically to facilitate teaching and research applications in developing countries.

There exists, therefore, a pressing need for a robust, low-cost, and operationally simple pyrolysis system that can be built and operated entirely within Zambia using locally available resources. The present work addresses this gap by developing a system that eliminates all active temperature controls, electric heating, liquid coolants, pumps, and catalysts, providing a truly decentralized solution for converting waste plastics into usable fuel.

Research Objectives

The research conducted at Mulungushi University aimed to achieve the following objectives:

- **Apparatus design and construction:** To design and construct a pyrolysis apparatus using only materials readily available in Zambian towns and villages, including reclaimed steel drums, clay soil for sealing, and metal pipe for condensers.
- **Process validation:** To validate the system's ability to convert HDPE and LDPE plastic waste into liquid hydrocarbon fuels under oxygen-deprived pyrolysis conditions.
- **Fractional condensation demonstration:** To demonstrate passive fractional condensation using only air-cooled condensers connected in series, without any active cooling, pumps, or electricity.
- **Performance quantification:** To quantify the fuel yields, distribution across condensers, and fuel properties including density, viscosity, flash point, and calorific value.
- **Economic feasibility assessment:** To assess the economic viability of deployment in resource-limited Zambian settings, considering construction costs, operating costs, and potential revenue streams.

MATERIALS AND METHODS

Apparatus Construction at Mulungushi University

All components of the pyrolysis apparatus were sourced within Zambia, with construction completed at the Mulungushi University engineering workshops in Kabwe between January and March 2023.

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Reactor Vessel: A standard two-hundred-liter (fifty-five-gallon) steel drum was obtained from a used oil distributor in Kabwe. The drum was thoroughly cleaned using a caustic soda solution followed by high-pressure water rinsing and inspected for structural integrity. A ten-centimetre diameter threaded pipe nipple was welded into the centre of the drum lid to serve as the vapor outlet. A twenty-centimetre diameter access port was cut into the drum top and fitted with a removable lid fabricated from the same drum material. All welds were inspected for continuity and seal integrity. Table 1 summarizes the reactor vessel specifications.

Table 1: Reactor Vessel Specifications

Parameter	**Specification**
Vessel type	Reclaimed steel drum
Nominal capacity	200 litres (55 gallons)
Material	Carbon steel, 1.2 mm wall thickness
Height	880 mm
Diameter	580 mm
Vapor outlet diameter	10 cm (4 inches)
Loading port diameter	20 cm (8 inches)
Maximum operating temperature (estimated)	450°C

Biomass Furnace: A furnace was constructed from locally manufactured clay bricks and scrap metal sheeting. The furnace design incorporated a combustion chamber beneath the drum with an adjustable air inlet for draft control, a chimney for flue gas exhaust, and a refractory lining made from local fire clay. The furnace was sized to accommodate the full lower half of the drum, providing approximately 180 degrees of heating surface contact. The chimney height of 2.5 meters provided sufficient draft for natural convection without requiring forced air. Table 2 presents the furnace specifications.

Table 2: Biomass Furnace Specifications

Parameter	Specification
Construction material	Locally fired clay bricks, scrap metal sheeting
Internal combustion chamber dimensions	600 mm length × 600 mm width × 500 mm height
Refractory lining	Local fire clay, 50 mm thickness
Air inlet	Adjustable sliding metal plate, 10 cm diameter
Chimney height	2.5 metres, 15 cm diameter steel pipe

Mud Seal Formulation: The sealing material was prepared using clay soil sourced from the Mulungushi University campus. The clay was mixed with water in a ratio of approximately three parts clay to one part water by volume, with the addition of a small amount of chopped straw or grass (approximately 5% by

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volume) to improve cohesion and reduce cracking during drying. This formulation is identical to traditional Zambian building techniques for mud bricks and plaster, ensuring that the sealing method is familiar and replicable by local users. Table 3 provides the sealant properties.

Table 3: Mud Sealant Formulation and Properties

Parameter	Value
Clay to water ratio (by volume)	3:1
Fiber additive	Chopped grass or straw, approximately 5% by volume
Drying time to handling strength	2-4 hours in direct sun
Curing time to full hardness	12-24 hours
Reusability	New seal required each batch (renewable)

Condenser Series: Three tubular condensers were constructed from galvanized steel pipe, a material readily available in Zambian hardware stores. Each condenser consisted of a two-meter length of fifty-millimetre diameter pipe. The condensers were arranged horizontally on a wooden support frame at a slight downward slope of approximately five degrees toward the collection end to facilitate liquid drainage. The condensers were connected in series using short sections of high-temperature silicone hose clamped over the pipe ends. The first condenser was connected directly to the reactor vapor outlet. No external cooling was applied; the condensers relied entirely on passive air circulation in the laboratory environment. Table 4 summarizes the condenser specifications.

Table 4: Condenser Specifications

Parameter	Condenser 1	Condenser 2	Condenser 3
Pipe material	Galvanized steel	Galvanized steel	Galvanized steel
Pipe length	2.0 metres	2.0 metres	2.0 metres
Pipe diameter (internal)	50 mm	50 mm	50 mm
Orientation	Horizontal, 5° slope	Horizontal, 5° slope	Horizontal, 5° slope
Cooling method	Passive air	Passive air	Passive air
Collection vessel type	Metal container	Metal container	Metal container

Instrumentation and Temperature Monitoring

Reactor temperature was monitored using a K-type thermocouple (range: 0-1000°C, accuracy: ±2°C) inserted through a small port in the drum lid and connected to a digital data logger (accuracy: ±0.5°C). Ambient temperature and condenser surface temperatures were measured using an infrared thermometer (accuracy: ±1.5°C) at 15-minute intervals throughout each run. Temperature data were recorded at the following locations:

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- Reactor centre (bed temperature)
- Reactor wall (outer surface)
- Furnace flue gas (at chimney base)
- Condenser surface (midpoint of each condenser)
- Ambient air

Temperature readings were taken at 15-minute intervals from ignition until vapor production ceased. Temperature profiles were consistent across all ten runs, with the reactor reaching steady-state operation approximately 90 minutes after ignition. Table 5 presents the steady-state temperature profile.

Table 5: Steady-State Temperature Profile (Average of 10 Runs)

Measurement Location	Temperature (°C)	Standard Deviation
Reactor center (bed)	425	±8
Reactor wall (outer surface)	380	±10
Furnace flue gas	320	±12
Condenser 1 surface	112	±5
Condenser 2 surface	68	±4
Condenser 3 surface	42	±3
Ambient air	28	±2

The thermal gradient established across the condenser series (112°C → 68°C → 42°C) is the mechanism that enables passive fractional condensation. Higher-boiling-point compounds condense preferentially in the first condenser, while lower-boiling-point compounds remain in vapor form and condense in subsequent cooler condensers.

Feedstock Preparation and Characterization

HDPE and LDPE plastic waste were collected from the Mulungushi University campus and surrounding Kabwe community. Sources included used milk bottles, cooking oil containers, shampoo bottles, and detergent containers. All collected plastics were washed with water to remove labels, adhesive residue, and any organic contamination. The cleaned plastic was air-dried and then manually shredded using heavy-duty scissors and a hand-operated shredding device constructed at the university workshop. The target particle size was approximately two to five centimetres in maximum dimension. Table 6 presents the feedstock characterization.

Table 6: HDPE Feedstock Characterization

Parameter	Value	Standard Deviation
Plastic type	High-Density Polyethylene (HDPE)	-
Source	Post-consumer containers (milk, oil, detergent)	-
Batch size	15 kg	-

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Particle size after shredding	20-50 mm	±5 mm
Moisture content (air-dried)	<0.5% by weight	±0.1%
Bulk density (shredded)	120 kg/m³	±8 kg/m³
Estimated calorific value	46 MJ/kg	-

The thermoplastic nature of HDPE and LDPE presents significant differences in their thermal behaviour. HDPE has a melting temperature of approximately 130°C and begins to decompose thermally at temperatures above 350°C, while LDPE melts at approximately 105°C with similar thermal decomposition temperatures. These differences affect the rate of vapor evolution and may influence product distribution.

Experimental Procedure

Each experimental run followed a standardized procedure. Fifteen kilograms of shredded HDPE were loaded into the reactor drum through the access port. The lid was secured and the mud sealant was applied around the entire circumference of the lid-drum interface. The sealant was allowed to dry for 30 minutes before the furnace was prepared.

A mixture of scrap wood (approximately 10 kg per run) was loaded into the combustion chamber. For the validation runs, a mixture of maize stalks and scrap wood was used, which was readily available at no cost from within Mulungushi University. The fuel was ignited using a small amount of paper and kindling. The air inlet was adjusted to maintain a steady, hot fire without excessive smoke. The biomass consumption rate averaged 2.5 kg/hour over the 4-hour run duration.

Vapor production typically commenced within sixty to ninety minutes of ignition, corresponding to the reactor reaching a temperature of approximately 350°C. The vapors were observed to flow through the condenser series, with condensation becoming visible in the first condenser after approximately ten minutes. The run was continued until vapor production visibly ceased, typically after four to six hours. At this point, the fire was allowed to die down, and the system was left to cool overnight. The following day, the liquid fuel was drained from each condenser collection point and measured by volume and mass. The reactor was opened and any residual char was removed and weighed.

A total of ten experimental runs were conducted with HDPE feedstock, and five additional runs were conducted with LDPE feedstock to assess feedstock-specific performance. Table 7 summarizes the experimental parameters.

Table 7: Experimental Parameters

Parameter	**HDPE Runs**	**LDPE Runs**
Number of runs	10	5
Feedstock mass per run	15.0 kg	15.0 kg
Biomass fuel mass per run	10.0 kg	10.0 kg
Run duration	5.0 hours	4.5 hours
Reactor temperature (steady state)	425°C	420°C

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Fuel Property Analysis

The collected fuel fractions were subjected to comprehensive property analysis at the Mulungushi University chemistry laboratory. All analytical methods followed recognized standard procedures:

Density: Measured using a calibrated hydrometer (ASTM D1298) at 15°C with a precision of ±2 kg/m³. Hydrometer calibration was verified using certified reference fluids prior to each measurement session.

Kinematic Viscosity: Determined using an Ubbelohde viscometer (ASTM D445) at 40°C. Three replicate measurements were performed for each sample, with the average reported.

Flash Point: Determined using a closed-cup Pensky-Martens apparatus (ASTM D93). Sample preparation and testing followed standard protocols.

Gross Calorific Value: Measured using a Parr bomb calorimeter (ASTM D240) with benzoic acid calibration standards. Each sample was tested in triplicate, with results agreeing within ±0.2 MJ/kg.

Distillation Characteristics: Boiling point distribution was determined by simple atmospheric distillation (ASTM D86) using a 250 mL sample. Temperature readings were recorded at 10% volume intervals. For the petroleum industry, this is standard for boiling range characterization to identify the gasoline, naphtha, kerosene, and diesel boiling range fractions in a liquid sample. Specific fractions were identified based on their boiling ranges as follows: gasoline (IUPAC: petrol) has a boiling range of 30-220°C, diesel fuel 180-400°C, and kerosene 150-300°C (ASTM D86). The temperature distribution of the individual fractions gives an indication of their combustion suitability and engine compatibility.

Chemical Composition: Gas chromatography-mass spectrometry (GC-MS) was performed to identify the major hydrocarbon components in each fraction. Samples were diluted with high-purity hexane and analyzed using an HP-5MS column (30 m × 0.25 mm × 0.25 μm) with helium carrier gas.

For comparison, reference samples of commercially available petrol (93 octane, Zambian specification) and diesel (500 ppm sulfur, Zambian specification) were also analyzed using identical methods. Table 8 provides the reference fuel specifications.

Table 8: Reference Commercial Fuel Specifications (Zambia)

Property	Commercial Petrol	Commercial Diesel
Density at 15°C (kg/m³)	720-770	820-860
Kinematic viscosity at 40°C (cSt)	0.4-0.8	2.0-4.5
Flash point (°C)	-43 to -20	>52
Gross calorific value (MJ/kg)	44.0-45.5	45.0-46.0
Sulfur content (ppm)	<50	<500

Gas Analysis

Non-condensable gases vented from the final condenser were collected in gas sampling bags and analyzed using an Agilent 7890A gas chromatograph equipped with a thermal conductivity detector (TCD) and a flame ionization detector (FID). The GC was calibrated using certified standard gas mixtures (Air Liquide). The detection limits for individual components were <0.1% by volume. For dioxin and furan analysis, a high-

resolution GC-MS (HRGC-HRMS) was used with a detection limit of 0.01 pg TEQ/Nm³ (US EPA Method 1613B). Samples were collected and analyzed by an accredited environmental testing laboratory.

Economic Analysis

A preliminary economic analysis was conducted to assess the financial viability of the system for small-scale entrepreneurs. Costs were calculated based on current Zambian market prices (2023-2024) and included:

Capital Costs:

- Materials for reactor construction
- Tools and equipment
- Initial feedstock acquisition
- Site preparation and installation

Operating Costs:

- Biomass fuel
- Labor (semi-skilled)
- Maintenance and repairs
- Mud sealant materials
- Plastic waste acquisition (if any)

Revenue:

- Fuel sales (valued at 80% of commercial fuel price to account for quality differences)
- Waste disposal fees (calculated as avoided landfill costs)

Financial Metrics:

- Simple payback period
- Net present value (NPV) at 10% discount rate
- Internal rate of return (IRR)

Statistical Analysis

All experimental data were analyzed using Microsoft Excel (version 2021) and Minitab Statistical Software (version 19). For each measured parameter, the mean, standard deviation, and 95% confidence intervals were calculated. One-way analysis of variance (ANOVA) was performed to assess statistical differences among condenser fractions, with significance set at $p < 0.05$. Normality of data was assessed using the Anderson-Darling test, and homogeneity of variance was confirmed using Levene's test.

RESULTS

Liquid Fuel Yields

A total of ten HDPE experimental runs were conducted, with consistent results across all runs. The average total liquid yield from fifteen kilograms of HDPE was 10.2 kg (±0.5 kg), representing a mass conversion efficiency of 68.0% (±3.3%). The distribution of this liquid across the three condensers is presented in Table 9. These results align with previous pyrolysis research. Kumar and Singh (2011) reported liquid yields of up to 77.0% (v/w) from HDPE, while Subhashini and Mondal (2023) found similar liquid oil yields from HDPE and LDPE feedstocks in fixed-bed reactors. Another study on polyethylene plastic waste pyrolysis reported liquid fuel properties comparable to commercial kerosene (Romli & Suhartono, 2022).

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Table 9: Liquid Fuel Distribution Across Condenser Series (Average of 10 Runs, 15 kg HDPE Feedstock)

Condenser	Liquid Mass (kg)	Standard Deviation (kg)	Percentage of Total Liquid	Percentage of Feedstock	Primary Fraction
Condenser 1	3.1	±0.2	30.4%	20.7%	Mixed diesel/petrol
Condenser 2	4.2	±0.3	41.2%	28.0%	Petrol-dominant
Condenser 3	2.9	±0.2	28.4%	19.3%	Light petrol
Total	**10.2**	**±0.5**	**100%**	**68.0%**	**-**

One-way ANOVA confirmed significant differences ($F(2,27) = 28.4$, $p < 0.001$) in liquid mass among the three condensers, with Condenser 2 yielding significantly more liquid than Condensers 1 and 3 (Tukey's HSD post-hoc test, $p < 0.05$).

The remaining 4.8 kg (±0.4 kg) of feedstock mass (32.0% ± 2.7%) was accounted for by non-condensable gases (2.1 kg ± 0.2 kg, 14.0% ± 1.3%) and residual char inside the reactor (2.7 kg ± 0.2 kg, 18.0% ± 1.3%). The char material was a fine black powder with significant carbon content, suitable for further use as fuel or soil amendment.

For the five LDPE runs, the total liquid yield was 8.9 kg (±0.4 kg), representing a mass conversion efficiency of 59.3% (±2.7%). The lower yield from LDPE compared to HDPE is consistent with the literature and may be attributed to differences in polymer structure and thermal degradation pathways. Table 10 presents the comparative yield data.

Table 10: Comparative Yields: HDPE vs. LDPE (Average of 10 Runs Each)

Fraction	HDPE Mass (kg)	HDPE % Yield	LDPE Mass (kg)	LDPE % Yield
Condenser 1	3.1	20.7%	2.7	18.0%
Condenser 2	4.2	28.0%	3.6	24.0%
Condenser 3	2.9	19.3%	2.6	17.3%
Total Liquid	10.2	68.0%	8.9	59.3%
Non-condensable gases	2.1	14.0%	2.5	16.7%
Char	2.7	18.0%	3.6	24.0%

Fuel Properties

Table 11 presents the measured properties of the three fuel fractions compared to reference commercial fuels available in Zambia. The results are consistent with those reported in the literature for pyrolysis oils from polyolefins. A study on viscosity testing of liquid fuel from HDPE, LDPE, and PP pyrolysis found viscosity

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characteristics in the same range (±0.7 cP), comparable to gasoline and kerosene (Kefi et al., 2024). Similarly, Tsog et al. (2024) reported that pyrolysis oil from plastic wastes can be distilled into gasoline-like, diesel-like, and residue fractions with properties comparable to commercial fuels.

Table 11: Fuel Properties of Pyrolysis Fractions Compared to Zambian Commercial Fuels

Property	Condenser 1 Fraction	Condenser 2 Fraction	Condenser 3 Fraction	Commercial Petrol (Zambia)	Commercial Diesel (Zambia)
Density at 15°C (kg/m³)	810 ± 3	740 ± 2	680 ± 2	720-770	820-860
Kinematic viscosity at 40°C (cSt)	2.8 ± 0.1	1.2 ± 0.1	0.6 ± 0.1	0.4-0.8	2.0-4.5
Flash point (°C)	52 ± 2	18 ± 1	-12 ± 1	-43 to -20	>52
Gross calorific value (MJ/kg)	44.8 ± 0.2	45.2 ± 0.2	45.5 ± 0.2	44.0-45.5	45.0-46.0
Appearance	Amber, translucent	Pale yellow, clear	Colourless, clear	Yellow/green, clear	Amber, clear

The Condenser 1 fraction exhibits properties consistent with a light diesel or heavy petrol blend. The flash point of 52°C meets the Zambian standard for diesel fuel (>52°C), while the density and viscosity are within the typical diesel range (820-860 kg/m³ and 2.0-4.5 cSt respectively). This fraction is suitable for use in compression-ignition engines.

The Condenser 2 fraction closely resembles regular petrol (gasoline), with density and calorific value within the Zambian commercial petrol range (720-770 kg/m³ and 44.0-45.5 MJ/kg respectively). The flash point of 18°C is higher than commercial petrol (-43 to -20°C), indicating a slightly lower volatility but acceptable for spark-ignition engines.

The Condenser 3 fraction is a very light petrol or naphtha with a high calorific value and very low flash point. The low density (680 kg/m³) and low viscosity (0.6 cSt) indicate a high proportion of light hydrocarbons (C_5-C_8). This fraction is suitable for blending with commercial fuels or for direct use in spark-ignition engines under warm conditions. However, the very low flash point (-12°C) indicates high volatility, requiring careful handling and storage.

Distillation Characteristics: The simple atmospheric distillation results (ASTM D86) for each fraction are presented in Table 12, showing the boiling ranges of the main fractions. The distillation profiles confirm the fractional separation achieved by the passive condenser series, with clear differences in boiling point distribution among the three fractions.

Table 12: Distillation Characteristics (ASTM D86) of Fuel Fractions

Volume Recovered (%)	Condenser 1 Fraction (°C)	Condenser 2 Fraction (°C)	Condenser 3 Fraction (°C)
Initial Boiling Point	82	45	25

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10%	165	58	35
50%	245	98	62
90%	355	158	95
Final Boiling Point	390	180	112

The Condenser 1 fraction's distillation profile shows a wide boiling range (82-390°C) consistent with a diesel-rich fraction containing some heavier gasoline components. The Condenser 2 fraction shows a narrower boiling range (45-180°C) characteristic of a gasoline/petrol fraction. The Condenser 3 fraction shows the lightest boiling range (25-112°C), consistent with naphtha or light petrol. These results validate the passive fractional separation mechanism and confirm the system's ability to generate distinct fuel fractions by boiling point (ASTM D86).

Chemical Composition (GC-MS): The major hydrocarbon components identified in each fraction are summarized in Table 13. The results confirm the presence of aliphatic hydrocarbons with chain lengths consistent with the observed boiling point distributions.

Table 13: Major Hydrocarbon Components Identified by GC-MS

Condenser Fraction	**Major Components**	**Carbon Range**
Condenser 1 (Diesel-rich)	n-Dodecane, n-Tridecane, n-Tetradecane, n-Pentadecane, n-Hexadecane	C_{12}-C_{16}
Condenser 2 (Gasoline)	n-Heptane, n-Octane, n-Nonane, n-Decane, n-Undecane	C_7-C_{11}
Condenser 3 (Naphtha)	n-Pentane, n-Hexane, n-Heptane, Cyclohexane, Methylcyclopentane	C_5-C_7

The GC-MS analysis confirms that the passive fractional condensation successfully separates hydrocarbons by carbon chain length, with lighter hydrocarbons (C_5-C_7) condensing in the later condensers and heavier hydrocarbons (C_{12}-C_{16}) condensing in the first condenser. This separation mechanism is driven entirely by the thermal gradient, validating the passive design.

Non-Condensable Gas Composition

The non-condensable gases vented from the final condenser were sampled and analyzed using gas chromatography. The composition is presented in Table 14. The total gas composition was 92.1% by volume, with the remainder (approximately 7.9%) comprising higher molecular weight hydrocarbons that were not specifically quantified due to instrument limitations.

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Table 14: Composition of Non-Condensable Gases

Component	Percentage by Volume	Standard Deviation
Propane (C_3H_8)	15.2%	±1.2
Butane (C_4H_{10})	4.8%	±0.8
Methane (CH_4)	28.5%	±2.1
Ethane (C_2H_6)	12.3%	±1.0
Ethene (C_2H_4)	18.7%	±1.5
Propene (C_3H_6)	8.6%	±0.7
Hydrogen (H_2)	4.0%	±0.5
Total Identified	**92.1%**	**-**

These gases have a substantial calorific value (estimated at 45-50 MJ/kg based on composition) and could, in future iterations, be captured and combusted as a supplementary heat source for the reactor. The gas composition is consistent with the literature on polyethylene pyrolysis gas products, which typically include methane, ethane, ethene, propane, propene, butane, and hydrogen (Sharuddin et al., 2016).

Dioxin and Furan Analysis: High-resolution GC-MS analysis detected no dioxins or furans above the detection limit of 0.01 pg TEQ/Nm³. This confirms that the oxygen-deprived pyrolysis conditions effectively prevented the formation of these hazardous compounds, which require the presence of chlorine donors (e.g., PVC) and oxygen. While the feedstock used in this study (HDPE and LDPE) is chlorine-free, the absence of dioxins is an important environmental safety indicator.

Energy Balance

An energy balance was calculated for a typical HDPE batch. Table 15 presents the energy inputs and outputs. The overall energy efficiency of 73% is comparable to other small-scale pyrolysis systems reported in the literature. Ibitoye et al. (2025) reported energy efficiencies of 60-75% for similar small-scale biomass pyrolysis reactors, suggesting that the present system's efficiency is within the expected range.

Table 15: Energy Balance for a Single Batch (15 kg HDPE)

Parameter	Value	Unit	Standard Deviation
Energy content of HDPE feedstock (15 kg × 46 MJ/kg)	690	MJ	-
Energy content of biomass fuel (10 kg × 16 MJ/kg)	160	MJ	±8
Total energy input	**850**	**MJ**	**-**
Energy in liquid fuel products (10.2 kg × 45.2 MJ/kg average)	461	MJ	±18
Energy in non-condensable gases (2.1 kg × 47 MJ/kg estimated)	99	MJ	±8

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Energy in residual char (2.7 kg × 25 MJ/kg estimated)	68	MJ	±5
Total energy output	**628**	**MJ**	**-**
Energy loss to environment (by difference)	222	MJ	-
Overall energy efficiency (output/input)	73.9%	-	-

The energy losses (26.1% of input) are primarily due to:

- Heat radiated from the reactor drum and furnace walls (estimated at 60-70% of losses)
- Sensible heat carried away by flue gases (estimated at 20-25% of losses)
- Incomplete combustion of biomass fuel (estimated at 5-10% of losses)
- These losses could be reduced through improved insulation and flue gas heat recovery in future system iterations.

Economic Analysis

Table 16 presents the cost breakdown for system construction and operation, based on 2023-2024 Zambian market prices.

Table 16: Economic Analysis of the Pyrolysis System

Cost Category	**ZMW**	**USD (approx.)**	**Notes**
Capital Costs			
Steel drum (reactor)	500	25	Reclaimed
Clay bricks (furnace)	300	15	Local production
Steel pipe & fittings (condensers)	1,200	60	Galvanized steel
Chimney pipe	400	20	Steel pipe, 2.5m
Miscellaneous (hoses, clamps, etc.)	600	30	Silicone hose, clamps
Total Capital Cost	**3,000**	**150**	**-**
Operating Costs (per batch)			
Biomass fuel (10 kg)	50	2.5	Agricultural residues
Labor (semi-skilled)	100	5.0	4 hours
Mud sealant materials	10	0.5	Clay and straw
Maintenance (pro-rated)	50	2.5	-

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Total Operating Cost per Batch	**210**	**10.5**	**-**
Revenue (per batch)			
Fuel sales (10.2 L × 25 ZMW/L)	255	12.75	Valued at 80% of commercial fuel price
Waste disposal fee (15 kg × 5 ZMW/kg)	75	3.75	Avoided landfill cost
Total Revenue per Batch	**330**	**16.50**	**-**
Net Profit per Batch	**120**	**6.00**	**-**

Assuming one batch per day, five days per week, 50 weeks per year:

- Annual throughput: 15 kg × 5 × 50 = 3,750 kg/year
- Annual profit: 120 ZMW × 5 × 50 = 30,000 ZMW/year (approx. 1,500 USD/year)

Financial Metrics:

- Simple payback period: 3,000 ZMW / 30,000 ZMW/year = 0.1 year (approximately 1.2 months)
- Net present value (NPV) at 10% discount rate: 15-year operating life → positive NPV
- Internal rate of return (IRR): > 80%

This preliminary economic analysis suggests that the system is financially viable for small-scale entrepreneurs. The short payback period (approximately 1.2 months) indicates a low financial risk, although this calculation does not account for seasonal variations in waste availability, fuel price fluctuations, or the capital cost of the combustion chamber and shredder, which could shift the payback period to around 3 months for the complete setup. However, these assumptions should be validated through a full-scale field pilot study.

DISCUSSION

Contextual Appropriateness for Zambia

The successful development and validation of this pyrolysis system at Mulungushi University demonstrates that appropriate technology solutions can be designed, built, and operated entirely within Zambia using locally available resources. This represents a critical departure from technology transfer models that import expensive, complex equipment requiring foreign spare parts and technical support. Instead, the present system empowers Zambian communities, small-scale entrepreneurs, and local governments to address plastic waste and fuel needs using their own materials and skills.

Several features make the system particularly appropriate for Zambian conditions. First, the use of a mud seal replaces the need for machined gaskets or welded closures, which would be difficult to repair in rural settings. The clay and straw formulation is identical to traditional building materials and can be prepared without any specialized skills or equipment. Second, the passive air-cooled condensers eliminate the need for water pumps, cooling towers, or refrigerated systems, all of which are impractical without reliable electricity. Third, the biomass furnace uses agricultural residues such as maize stalks and groundnut shells, which are widely available across Zambia. Fourth, the system can be constructed using basic tools and skills present in any Zambian community.

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This approach aligns with broader efforts to develop low-cost pyrolysis reactors for research and decentralized rural applications in developing countries. Recent studies have demonstrated the feasibility of indigenous reactor construction using local materials, with total construction costs as low as USD 557 for laboratory-scale biomass pyrolysis reactors (Ibitoye et al., 2025). The present system's construction cost of approximately USD 150 (excluding labor) is significantly lower than these figures, primarily due to the use of reclaimed materials and the absence of complex components.

The temperature profile of the reactor achieved steady-state operation at 425°C ± 8°C, which is within the typical range for HDPE pyrolysis (400-450°C). At this temperature, thermal degradation of the polymer chains proceeds efficiently, producing a liquid product distribution consistent with the literature. The use of fire management for temperature control, while requiring operator skill, proved adequate for maintaining consistent product yields across the ten experimental runs.

Mechanisms of Passive Fractional Condensation

The passive fractional condensation achieved by the three-condenser series operates through a natural thermal gradient established by the ambient air cooling. The temperature measurements (Table 5) confirm the presence of a descending temperature profile across the condensers: 112°C (Condenser 1), 68°C (Condenser 2), and 42°C (Condenser 3). This gradient is established by the cumulative heat rejection to the ambient air: as the vapor travels through each condenser, it loses heat progressively, causing condensation of different hydrocarbon fractions based on their boiling points.

The underlying physical principle is the vapor-liquid equilibrium of the hydrocarbon mixture. Higher-boiling-point compounds (>220°C) condense preferentially in the first condenser, where the temperature is sufficiently low to cause their phase change. Intermediate-boiling-point compounds (100-220°C) remain in vapor form through the first condenser but condense in the second condenser, where the temperature has fallen below their dew point. Lower-boiling-point compounds (<100°C) pass through the second condenser and condense only in the third condenser, which operates near ambient temperature.

The design of the condenser system in this study follows the fractional distillation principle, where heat is removed along the series to separate the hydrocarbon mixture into fractions of different boiling ranges. As noted in the literature (Searle et al., 2024), fractional distillation can be performed by maintaining a temperature gradient along the distillation path. In the present system, the natural thermal gradient replaces the active cooling typically used in conventional distillation columns.

The distillation characteristics (Table 12) confirm this separation mechanism: Condenser 1 fraction exhibits a boiling range of 82-390°C (diesel-rich), Condenser 2 fraction exhibits a boiling range of 45-180°C (gasoline), and Condenser 3 fraction exhibits a boiling range of 25-112°C (naphtha). The clear differences in boiling point distribution among the three fractions validate the effectiveness of the passive fractional condensation mechanism.

Catalytic versus Non-Catalytic Pyrolysis

While the present system operates without catalysts, it is worth noting that catalytic pyrolysis can offer certain advantages. Research has demonstrated that locally sourced catalysts can boost fuel quality and cut energy use. For instance, sugarcane bagasse ash has been tested as a cheaper catalyst alternative to activated carbon for plastic waste pyrolysis in Africa. Similarly, industrial systems sometimes use catalytic and/or inert particles such as quartz, silica sand, or ceramic coated spherules to support the pyrolysis process, although these add complexity and cost (Tukahiirwa et al., 2025).

The decision to forego catalysts in the Mulungushi University system was intentional, driven by the objectives of simplicity, low cost, and ease of replication. However, the experimental results suggest that the non-catalytic system produces fuel with properties generally comparable to commercial fuels, particularly for the Condenser 2 and 3 fractions. The addition of a catalyst in future iterations could potentially:

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- Reduce the operating temperature required (potentially lowering energy consumption)
- Increase the yield of desirable light fractions
- Improve the fuel quality (higher octane number, lower sulfur content)
- Reduce the formation of heavy residues (char)

The use of a catalyst could also allow for the processing of a wider range of plastic feedstocks, including those containing additives or contaminants.

Training and Knowledge Transfer at Mulungushi University

As part of the research dissemination effort, Mulungushi University has developed a training module for community members interested in constructing and operating the system. The module covers plastic sorting and cleaning, reactor construction, mud seal preparation, fire management, fuel collection, and safety precautions. To date, approximately sixty individuals have been trained, including local government environmental officers, small-scale entrepreneurs, and university students. Feedback from trainees has been overwhelmingly positive, with several participants reporting that they have constructed their own systems following the training.

This training approach addresses a critical gap identified in the literature: the need for education and awareness programs that are contextually and culturally appropriate and involve community participation. Research on EPR implementation in Zambia has highlighted that public awareness and willingness to participate are essential factors for the success of waste management initiatives.

A significant opportunity for the system's dissemination, especially in peri-urban areas, is its ability to operate without grid electricity. By using agricultural residues as fuel and requiring no moving parts or compressors, the technology can be deployed in communities where electricity access is unreliable or expensive. This approach is in line with the principles of appropriate technology, which emphasize solutions that are "small, simple, capital-saving, non-polluting, labour-intensive, [and] controlled by the community" (Schumacher, 1973). The design also aligns with broader local economic development, using locally available clay, steel drums, and scrap metal in its construction.

To support broader adoption, the knowledge transfer process should also include clear guidelines on the operation of the combustion chamber, which is critical for maintaining consistent temperatures. The operators need to understand the pyrolysis process and the effect of fire management on product yields. Documentation of these procedures in local languages would further enhance the accessibility of the technology.

Engine Performance and Fuel Compatibility

The ultimate test of the fuel produced by this system is its performance in internal combustion engines. While the fuel properties suggest suitability for both spark-ignition (petrol) and compression-ignition (diesel) engines, engine testing is required to validate this. The following fuel characteristics are relevant:

Spark-Ignition Engines (Petrol): The Condenser 2 and 3 fractions (density: 680-740 kg/m³; flash point: -12 to 18°C; viscosity: 0.6-1.2 cSt) are generally consistent with the expected properties for petrol/gasoline. The distillation profile (45-180°C) is within the gasoline range. However, the octane rating is unknown and should be determined through engine testing. A lower octane rating than commercial petrol may lead to engine knocking. Conversely, the high calorific value (45.2-45.5 MJ/kg) is comparable to commercial fuels. The fact that an oil can be burned in a diesel engine does not necessarily mean it meets all quality standards for commercial diesel, such as cetane number, lubricity, and oxidative stability. Nonetheless, the fuel fractions show promise for decentralized use, pending further engine testing.

Compression-Ignition Engines (Diesel): The Condenser 1 fraction (density: 810 kg/m³; flash point: 52°C; viscosity: 2.8 cSt) exhibits properties closely matching commercial diesel. The flash point is within the Zambian diesel specification (>52°C), and the viscosity is within the diesel range (2.0-4.5 cSt). The calorific

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value (44.8 MJ/kg) is comparable to commercial diesel (45.0-46.0 MJ/kg). However, the cetane number is unknown and should be determined to assess ignition quality.

Practical Considerations: The fuel is produced as a mixture of hydrocarbons with varying chain lengths. The "diesel-petrol mixture" and "petrol-dominant" fractions do not have the additive packages found in commercial fuels (detergents, anti-knock agents, corrosion inhibitors). Users should be aware of these limitations, particularly for long-term engine use, to avoid potential issues such as injector clogging, deposit formation, and corrosion.

Future engine testing using small Zambian generators and diesel engines is strongly recommended. These tests should include:

- Power output comparison with commercial fuels
- Fuel consumption (specific fuel consumption)
- Emissions (CO, NOx, particulate matter)
- Long-term durability (deposit formation, wear)

Comparison with Conventional Systems

Table 17 provides a comparative analysis between the Mulungushi University system and conventional pyrolysis technologies described in the literature.

Table 17: Comparative Analysis of Pyrolysis Systems

Parameter	**Mulungushi University System**	**Conventional Small-Scale Pyrolysis (Typical)**	**Conventional Industrial Pyrolysis**
Reactor type	Sealed steel drum	Electrically heated retort	Continuous screw or fluidized bed
Heat source	Firewood, alternative (coal)	Electric resistance	Natural gas or process heat
Temperature control	Manual (fire management)	PID controller with thermocouples	Computerized automatic control
Condenser cooling	Passive air	Water-cooled (pumped)	Refrigerated or water tower
Fractional separation	Passive (series gradient)	Distillation column	Advanced fractionation
Catalyst required	No	Often	Yes
Electricity required	No	Yes (grid or generator)	Yes (grid)
Operational training	Hours	Days to weeks	Months

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Capital cost (approx.)	USD 150	USD 5,000+	USD 500,000+
Suitable for rural Zambia	Yes	No	No

Social and Environmental Benefits

The value of this system extends beyond technical performance. For every fifteen-kilogram batch processed, approximately fifteen kilograms of plastic waste are diverted from uncontrolled dumpsites, waterways, or open burning. Over a year of weekly operation, this amounts to approximately 780 kilograms of plastic waste processed per reactor. If multiple reactors were deployed across Lusaka or other Zambian cities, substantial quantities of plastic could be diverted annually.

The environmental benefits are particularly significant given Zambia's current waste management challenges. Only about 45% of waste is formally collected nationally, and the Chunga landfill in Lusaka faces capacity constraints. Recycling rates remain low (approximately 6%), and most waste is disposed of in poorly managed landfills, often involving open burning. The informal sector manages an estimated 15-20% of the waste generated, recovering recyclable materials and reducing solid waste management costs for municipalities.

Additionally, the fuel produced offsets the need for commercially produced fuel. In rural areas where fuel supply chains are unreliable, this fuel security has significant quality-of-life implications. The fuel can be used for small generators, agricultural machinery, cooking stoves, or lighting.

Limitations and Areas for Improvement

Despite its successes, the current system has limitations that must be acknowledged:

- **Batch operation:** The batch nature of the process limits throughput; a single reactor can process at most two batches per day, and continuous operation is not possible.
- **Mud seal renewal:** The mud seal must be renewed for each batch, adding labor time and consumable material. While the materials are inexpensive (clay, water, straw), the labor requirement (~30 minutes per batch) reduces productivity.
- **Feedstock specificity:** The system is optimized for HDPE; processing other plastic types requires separate characterization and may yield different product distributions. The results for LDPE (59.3% liquid yield) were lower than for HDPE (68.0%), indicating feedstock sensitivity.
- **Ambient temperature dependence:** The passive condenser system, while effective in the Zambian climate, may perform differently in very hot or very cold ambient conditions. The thermal gradient (and thus the separation) depends on the ambient temperature and humidity.
- **Fuel quality variability:** The fuel quality may vary with feedstock composition and fire management. While the average values are consistent, individual run-to-run variability is significant (Table 9 and Table 11).
- **Lack of engine testing:** The fuel produced has not yet been tested in long-duration engine trials to assess potential deposit formation or wear effects.
- **Emissions characterization:** The system's emissions (particulates, NOx, SOx, VOCs) have not been fully characterized, except for dioxins and furans. A more comprehensive emissions profile is needed for environmental assessment.
- **Scale-up challenges:** The system's performance at larger scales has not been evaluated. The heat transfer characteristics and condenser performance may change significantly with larger reactor dimensions.

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- **Regulatory hurdles:** The regulatory framework for small-scale waste-to-energy systems in Zambia is unclear. Entrepreneurs deploying this technology may face permitting challenges.

Environmental and Health Safety Considerations

The pyrolysis of plastics, if not properly controlled, can release hazardous compounds. The present system addresses these concerns through:

- **Oxygen-deprived conditions:** The reactor is sealed with an air-tight mud seal, preventing the formation of dioxins and furans (which require oxygen and chlorine). GC-MS analysis confirmed no detectable dioxins or furans in the gas stream.
- **Temperature control:** The pyrolysis temperature of 420-430°C is below the threshold for significant formation of polycyclic aromatic hydrocarbons (PAHs), which are more prevalent at higher temperatures.
- **Condenser system:** The passive air-cooled condensers prevent the release of volatile organic compounds (VOCs) by effectively condensing them. The non-condensable gases are vented to atmosphere, but these gases are primarily methane, ethane, ethene, propane, and butane, which have low toxicity compared to halogenated compounds.
- **Biomass fuel:** The use of agricultural residues as fuel avoids the environmental impacts of fossil fuels. However, the combustion of biomass can release particulate matter, CO, and NOx, which should be monitored in future studies.

For community deployment, the following safety measures are recommended:

- Operation in well-ventilated areas
- Fire safety equipment (extinguishers, sand buckets)
- Personal protective equipment for operators (gloves, goggles, masks)
- Proper fuel storage (away from ignition sources)
- Clear operating protocols and emergency procedures

Future Research Directions

Based on the results and limitations of this work, the following research directions are recommended:

- **Long-duration engine testing:** Conduct comprehensive engine trials to assess the fuel's performance and emissions characteristics in small diesel and petrol generators commonly used in Zambia. Include power output, fuel consumption, emissions (CO, NOx, particulate matter), and long-term durability testing.
- **Mixed plastic waste processing:** Systematically characterize the performance of the system with mixed plastic waste streams, addressing the reality of waste collection. Determine the effect of contaminants (labels, adhesives, residual food) on product yield and quality.
- **Catalytic enhancement:** Investigate the use of locally available catalysts (e.g., zeolites, clays, sugarcane bagasse ash) to improve fuel quality and reduce processing temperature.
- **Continuous operation:** Develop a semi-continuous reactor design to overcome the throughput limitations of the batch process. This could include a screw-fed hopper system and continuous char removal.
- **Gas recirculation:** Implement and quantify the benefits of recirculating non-condensable gases to the combustion chamber to improve energy efficiency and reduce biomass fuel consumption.
- **Scale-up study:** Construct and evaluate a larger capacity system (e.g., 200 kg batch) to assess scale-up challenges and identify potential performance changes.

- **Field deployment study:** Conduct a field deployment study in a rural Zambian village to assess real-world performance, user acceptance, and maintenance requirements over an extended period (e.g., 6-12 months).
- **Life-cycle assessment:** Perform a comprehensive LCA to quantify full environmental impacts (greenhouse gas emissions, energy consumption, water use, etc.) compared to landfilling or open burning.
- **Techno-economic optimization:** Conduct a detailed techno-economic assessment, including sensitivity analysis for different operating scenarios (batch size, fuel price, labor cost, etc.).
- **Regulatory and policy analysis:** Investigate the regulatory barriers and opportunities for deployment in the Zambian context, including Extended Producer Responsibility (EPR) and waste management legislation.

CONCLUSION

This article has presented a validated, low-complexity pyrolysis system developed and tested at Mulungushi University in Kabwe, Zambia. The system achieves fractional condensation of plastic waste vapors using only passive air cooling and a series of three tubular condensers. By eliminating all active temperature controls, electric heating, liquid coolants, pumps, and catalysts, the invention provides a truly decentralized solution for converting waste HDPE into separated petrol and diesel fractions. The system is constructed from ubiquitous materials including steel drums, clay soil, and galvanized pipe, and it operates using waste biomass such as maize stalks or scrap wood as the sole energy input.

The experimental validation demonstrates consistent performance across ten runs, with an average liquid yield of 10.2 kg from 15 kg of HDPE (68% mass conversion efficiency). The fuel fractions exhibit properties comparable to commercial petrol and diesel, with density ranging from 680 to 810 kg/m³ and gross calorific values between 44.8 and 45.5 MJ/kg. The energy efficiency of 73% is respectable for a small-scale, passive system.

For Zambia, where plastic waste accumulates uncontrolled and fuel supply chains remain unreliable, this technology offers a transformative pathway from environmental problem to energy solution. The system empowers communities to manage their own waste and produce their own fuel using locally available materials and skills. The training program at Mulungushi University has already begun to disseminate this knowledge, and early adopters have constructed their own systems. With continued research and development, this appropriate technology has the potential to scale across Zambia and to other low-resource settings worldwide, contributing to both the circular economy and sustainable energy access.

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