



Development and performance evaluation of an innovative community-scale single-pillar pyrolysis reactor for converting plastic waste into alternative liquid fuel

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Abstract

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Plastic waste accumulation has become a critical global environmental challenge due to the increasing generation of non-recyclable plastics and the growing demand for sustainable waste-to-energy technologies. This study developed and evaluated an innovative community-scale single-pillar pyrolysis reactor for converting non-recyclable polypropylene (PP) and polystyrene (PS) waste into alternative liquid fuel under catalyst-free, oxygen-limited conditions. The system integrates a pyrolysis chamber, an externally heated combustion chamber fueled by waste lubricating oil, a vertical water-cooled condenser, and a vapor-recycling unit into a compact configuration suitable for decentralized applications. Reactor performance was evaluated using two PP:PS feedstock compositions (50:50 and 60:40, w w⁻¹). Each batch processed 10 kg of plastic waste (n = 3), producing 8.03 – 8.27 L of pyrolysis oil within 190 – 200 min. The 60:40 feedstock yielded numerically higher liquid fuel production (67.00 ± 1.91 wt.%), fuel conversion efficiency (73.85 ± 2.31%), oil productivity (3.73 ± 0.23 L h⁻¹), and higher heating value (45.73 ± 0.23 MJ kg⁻¹), together with a lower estimated gas yield (23.73 ± 2.16 wt.%). However, these differences were not statistically significant (*p* > 0.05), indicating stable and reproducible reactor performance across both feedstock compositions. Field validation following technology transfer was conducted in 19 communities in Loei Province, Thailand. The system achieved an average plastic reduction efficiency of 92.96 ± 0.87%, reduced accumulated plastic waste by 55.51 ± 22.41%, and demonstrated successful utilization of the recovered fuel in agricultural machinery and municipal crematoriums. These findings demonstrate that the proposed single-pillar reactor provides a practical, low-cost, and scalable decentralized waste-to-energy technology that supports circular economic implementation and sustainable community-based plastic waste management.

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1. Introduction

Plastic waste has become one of the most pressing environmental challenges worldwide owing to the rapid growth in plastic production and the limited capacity of existing waste-management systems. Plastics are extensively used in packaging, consumer products, agriculture, transportation, and industrial applications because of their low cost, lightweight structure, durability, and versatility. However, these same properties also contribute to their long persistence in the environment when discarded or inadequately managed. According to the Organization for Economic Co-operation and Development (OECD), global plastic production exceeded 460 million

tons annually, generating more than 350 million tons of plastic waste, while less than 10% was effectively recycled [1]. Consequently, large quantities of plastic waste continue to accumulate in landfills or are openly burned and released into terrestrial and aquatic ecosystems, contributing to greenhouse gas emissions, microplastic pollution, ecosystem degradation, biodiversity loss, and increasing risks to human health [2, 3]. In parallel with the growing plastic-waste crisis, fluctuations in global energy markets and rising petroleum-fuel prices have increased economic pressure on energy-dependent sectors, particularly agriculture and local public services in developing countries. In Thailand, gasoline and diesel are extensively

consumed for agricultural machinery, irrigation pumps, transportation, and municipal operations, making local communities increasingly vulnerable to fuel-price instability. These interconnected environmental and energy challenges highlight the need for decentralized waste-to-energy technologies capable of simultaneously reducing non-recyclable plastic waste and recovering its embedded energy. Converting locally available plastic waste into alternative liquid fuel therefore represents a promising approach for reducing environmental burdens, improving local energy resilience, and supporting circular economy implementation and sustainable resource management.

Among the available waste-to-energy technologies, pyrolysis has emerged as one of the most promising thermochemical processes for converting non-recyclable plastic waste into valuable liquid oil, combustible gases, and carbonaceous solid residues under oxygen-free or oxygen-limited conditions. Compared with conventional incineration, pyrolysis enables the recovery of the chemical energy embedded in plastic waste as transportable fuels and chemical feedstocks, thereby providing greater flexibility for resource recovery, greenhouse-gas mitigation, and circular-economy applications [4 – 6]. The distribution, yield, and physicochemical properties of the pyrolysis products are strongly influenced by feedstock composition, reactor configuration, operating temperature, heating rate, vapor residence time, and condensation efficiency, all of which govern the extent of primary decomposition and secondary cracking reactions during thermal conversion [7, 8]. Consequently, recent research has increasingly focused on optimizing reactor design, heat-transfer performance, and process operating conditions to maximize liquid-fuel recovery, improve product quality, and enhance the overall energy efficiency of plastic pyrolysis systems [6, 7]. Among the various plastic feedstocks, polypropylene (PP) and polystyrene (PS) are particularly attractive because of their high hydrocarbon content and favorable thermal degradation characteristics. PP primarily decomposes into aliphatic hydrocarbons, whereas PS predominantly produces aromatic compounds rich in styrene, suggesting that blending these polymers may influence both liquid yield and fuel quality [4, 9].

Previous studies have reported liquid-fuel yields approaching 90 wt.% with higher heating values of approximately 40 – 46 MJ kg⁻¹, comparable to those of conventional petroleum fuels, although the actual product distribution depends on reactor design and operating conditions [10 – 12]. These characteristics demonstrate that PP-PS mixtures are promising feedstocks for decentralized waste-to-fuel systems capable of producing high-energy alternative liquid fuels. Recent advances in plastic pyrolysis have increasingly focused on catalytic pyrolysis, co-pyrolysis, and reactor optimization to improve liquid-fuel quality and product selectivity. Various catalysts, including zeolites, fluid catalytic cracking (FCC) catalysts, metal oxides, biochar-based catalysts, and waste-derived carbonaceous materials, have been employed to promote secondary cracking, aromatization, and deoxygenation

reactions, thereby increasing the production of valuable hydrocarbons and improving the physicochemical properties of pyrolysis oil [7, 13 – 16]. In addition, co-pyrolysis of plastics with biomass or other carbonaceous materials has been reported to generate synergistic interactions between pyrolysis volatiles, thereby modifying secondary vapor-phase reactions, improving hydrocarbon selectivity, suppressing undesirable oxygenated compounds, and enhancing liquid-fuel quality [16 – 19]. Despite these advantages, catalyst-assisted and co-pyrolysis systems generally require additional feedstock preparation, catalyst activation and regeneration, process control, and higher operating costs, which may limit their applicability in decentralized or community-scale waste-management systems. For practical implementation, particularly in rural communities and local municipalities, reactor simplicity, low construction cost, ease of operation, and minimal maintenance are often more important than maximizing product selectivity. Consequently, catalyst-free thermal pyrolysis remains an attractive and practical option for converting locally available non-recyclable plastic waste into alternative liquid fuel under community-scale operating conditions.

Reactor configuration is a key engineering factor governing heat transfer, vapor residence time, product distribution, operational stability, and process scalability during plastic pyrolysis. Various reactor designs, including fixed-bed, fluidized-bed, rotary-kiln, auger, and conical spouted-bed reactors, have been developed to improve conversion efficiency and product quality. Fixed-bed reactors are widely applied in laboratory studies because of their simple construction and low investment cost, whereas fluidized-bed and continuous reactors generally provide superior heat transfer, mixing efficiency, and process control for large-scale operation [20, 21]. However, these advanced reactor systems often require sophisticated feeding mechanisms, carrier gases, moving components, precise process control, and higher capital and maintenance costs, limiting their practical implementation in decentralized applications [22]. Similarly, recent developments in catalytic reactor technologies have demonstrated significant improvements in product selectivity and conversion efficiency; however, these systems remain technically sophisticated and are primarily designed for industrial-scale operation, thereby limiting their applicability in small-scale decentralized communities [23]. Therefore, there remains a need for a simple, low-cost community-scale reactor that can be fabricated from locally available materials while providing stable operation, efficient heat transfer, and high liquid-fuel production.

Despite significant advances in plastic pyrolysis, a substantial gap remains between laboratory research and practical community-scale implementation. Previous studies have mainly focused on reaction optimization, catalysts, product yield, and fuel characterization under laboratory conditions [24, 25], whereas simplified, locally fabricated reactors with comprehensive evaluations of reactor performance, economic feasibility, practical fuel

utilization, and field validation remain limited [22]. To address this gap, this study developed and evaluated a catalyst-free community-scale single-pillar batch pyrolysis reactor for converting non-recyclable PP and PS waste into alternative liquid fuel. Reactor performance, fuel properties, and practical applicability were validated through technology transfer in 19 local communities. The novelty lies in integrating simplified reactor engineering, comprehensive performance evaluation, and multi-site community implementation in Appendix A (Table A1).

2. Materials and Methods

Reactor Design and Fabrication

An innovative community-scale single-pillar pyrolysis reactor was designed and fabricated at Loei Rajabhat University, Thailand, for converting non-recyclable polypropylene (PP) and polystyrene (PS) waste into alternative liquid fuel under oxygen-limited, catalyst-free conditions. The overall reactor configuration and operating principle are illustrated in Fig. 1 and Fig. 2, while the principal engineering specifications are summarized in Table 1. The system comprises nine integrated components: ① reaction vessel, ② vapor transfer pipe, ③ vertical water-cooled condenser, ④ oil outlet, ⑤ return gas pipe, ⑥ combustion chamber, ⑦ DC blower, ⑧ temperature gauge, and ⑨ cooling-water circulation system. Constructed primarily from 4 × 4 in. and 5 × 5 in. square steel sections with standard 1/2- and 3/4-in. steel pipes, the

reactor provides a robust and durable structure suitable for community-scale operation. During operation, mixed plastic feedstock is loaded into the reaction vessel and thermally decomposed by indirect heating from an externally fired combustion chamber fueled with waste lubricating oil.

The generated vapors flow through the transfer pipe to the vertical water-cooled condenser, where circulating cooling water promotes hydrocarbon condensation to produce liquid fuel, while the remaining non-condensable gases are recirculated to the combustion chamber and combusted with air supplied by a 12-V DC blower, thereby improving thermal efficiency and reducing gaseous emissions. Process temperature is continuously monitored throughout the operation. Unlike conventional laboratory-scale pyrolysis systems employing multiple condensers, auxiliary tanks, or mechanically driven circulation units, the proposed reactor integrates reaction, vapor transport, condensation, gas recirculation, and heat recovery into a compact single-pillar configuration. This simplified engineering design minimizes pipe connections and pressure losses, facilitates fabrication and maintenance, and maintains stable batch operation without catalysts, carrier gases, or mechanical agitation. With a processing capacity of approximately 10 kg of plastic waste per batch, the reactor is well suited for decentralized plastic waste management and alternative fuel production in rural and community-scale applications.

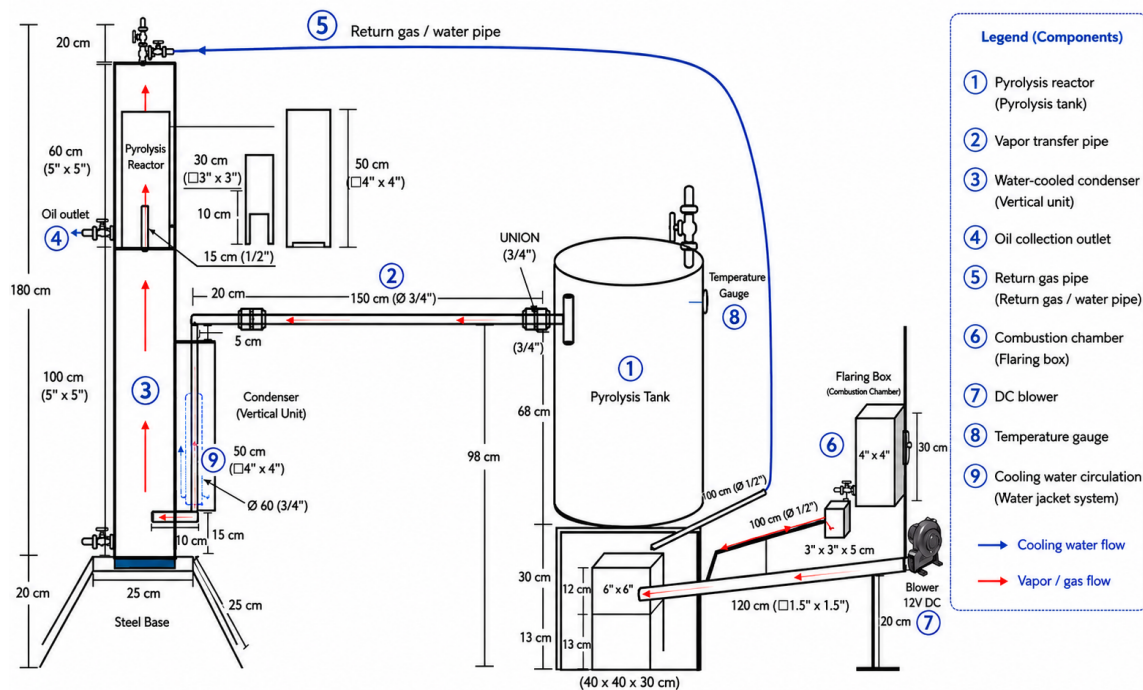


Fig. 1 Engineering schematic of the community-scale single-pillar pyrolysis reactor, showing its configuration and dimensions.



Fig. 2 Photograph of the fabricated prototype of the community-scale single-pillar pyrolysis reactor.

Table 1 Design specifications of the proposed community-scale single-pillar pyrolysis reactor.

Component	Engineering specification	Material / Dimension	Function
Pyrolysis reactor	Batch-type cylindrical reactor	Ø 68 cm × H 98 cm	Thermal decomposition of plastic waste under oxygen-limited conditions
Reactor lid	Airtight removable lid with pressure-relief valve	Carbon steel	Prevents oxygen infiltration and ensures operational safety
Temperature monitoring	Analog temperature gauge	Installed on reactor wall	Monitors reactor temperature during operation
Heating system	External combustion chamber using waste lubricating oil	Steel combustion box	Provides indirect heating without direct flame contact
Vapor transfer pipe	Threaded steel pipe	Ø 3/4 in.; Length 150 cm	Transfers hydrocarbon vapor to condenser
Union joint	Threaded union	Ø 3/4 in.	Facilitates assembly and maintenance
Water-cooled condenser	Vertical single-pillar condenser	Square steel column (□ 5 × 5 in.); H 180 cm	Condenses hydrocarbon vapor into liquid fuel
Cooling jacket	Water-cooling jacket	□ 4 × 4 in.; H 50 cm	Removes heat from vapor stream
Internal vapor tube	Vertical vapor guide	□ 3 × 3 in.; H 30 cm	Directs vapor upward to increase condensation efficiency
Oil collection outlet	Collection valve	1/2 in.	Collects condensed pyrolysis oil
Cooling-water circulation	Continuous water circulation	Ø 3/4 in.	Maintains condenser temperature
Return gas pipe	Gas recirculation pipe	Ø 1/2 in.; Length 60 cm	Returns non-condensable gas to combustion chamber
Combustion chamber (Flaring box)	Secondary combustion chamber	□ 4 × 4 in.; H 30 cm	Burns recovered gases and heating fuel
Fuel supply tank	Waste lubricating oil reservoir	□ 4 × 4 in.	Stores heating fuel
Fuel transfer pump	DC diaphragm pump	12 V	Supplies waste oil to burner
Supporting frame	Welded steel frame	40 × 40 × 30 cm	Supports reactor safely

Feedstock Preparation and Experimental Design

Non-recyclable polypropylene (PP) and polystyrene (PS) wastes were collected from community waste-sorting centers in Loei Province, Thailand. Feedstock preparation involved manual collection, polymer sorting, washing, air drying, blending, and compaction before pyrolysis, as illustrated in Fig. 3. Collected plastic wastes were manually sorted to remove non-plastic materials and separate PP and PS from other polymer types. After washing with clean water to remove adhering dirt and contaminants, the selected plastics were air-dried under ambient conditions for approximately 24 h. The dried materials were blended to obtain two feedstock compositions with PP:PS mass ratios of 50:50 and 60:40 ($w\ w^{-1}$), then compressed into 1-kg blocks to facilitate handling, storage, and uniform loading. For each experimental run, 10 blocks (10 kg) were loaded into the reactor. Experiments were conducted using a completely randomized design (CRD) consisting of two feedstock compositions with three independent replicates per treatment. Throughout the study, reactor configuration, heating system, operating procedure, cooling conditions, and analytical protocols were maintained constantly, with feedstock composition as the only experimental variable. Detailed operating conditions are presented in Table 2.

Pyrolysis Operating Procedure

The pyrolysis experiments were conducted under the operating conditions summarized in Table 2. For each run, 10 kg of compressed plastic feedstock was loaded into the reactor, and the lid was tightly sealed to maintain oxygen-limited conditions. Waste lubricating oil was used as the heating fuel, and the burner was preheated for 3–5 min before heating the reactor. The reactor was operated at 200–500 °C, with temperature controlled by adjusting the airflow from the 12-V DC blower and the waste-oil supply rate. The generated vapors were condensed in the water-cooled condenser, and the times to first oil production and first combustible gas generation were recorded. Pyrolysis oil was collected in glass bottles, while non-condensable gases were returned to the combustion chamber as supplementary fuel. Heating was discontinued after 210 – 240 min, or when vapor generation became negligible. The reactor was cooled naturally for approximately 60 min before the char was removed, weighed, and recorded. Each feedstock condition was tested in triplicate ($n = 3$).

Engineering Performance Evaluation

The engineering performance of the developed community-scale single-pillar pyrolysis reactor was evaluated using the experimental data obtained from each pyrolysis run. The evaluated parameters included the maximum reactor temperature, operating time, time to first oil production, time to first combustible gas generation, liquid fuel yield, solid residue yield, estimated non-condensable gas yield, plastic reduction efficiency (PRE), and fuel conversion efficiency (FCE). All calculations were

performed using the following equations.

Plastic reduction efficiency

Plastic reduction efficiency (PRE) was calculated as the percentage reduction in solid plastic residue after pyrolysis using Equation (1) [4, 10].

$$PRE(\%) = \frac{W_i - W_r}{W_i} \times 100 \quad (1)$$

where W_f is the initial feedstock mass (kg) and W_c is the mass of the recovered solid residue (kg).

Volumetric liquid fuel yield

The product yield was evaluated based on the mass distribution of liquid fuel, solid residue (char), and estimated non-condensable gas generated during the pyrolysis process. The liquid fuel and solid residue yields were determined gravimetrically, whereas the non-condensable gas yield was estimated by mass balance using Equations (2) – (4) [4, 8].

Liquid fuel yield

$$\text{Liquid fuel yield (\%)} = \frac{W_o}{W_f} \times 100 \quad (2)$$

where W_o is the mass of the collected liquid fuel (kg) and W_f is the initial feedstock mass (kg).

Solid residue yield

$$\text{Solid residue yield (\%)} = \frac{W_c}{W_f} \times 100 \quad (3)$$

where W_c is the mass of the recovered solid residue (char) (kg).

Estimated non-condensable gas yield

$$Y_G = 100 - Y_L - Y_C \quad (4)$$

where Y_G is the estimated non-condensable gas yield (%), Y_L is the liquid fuel yield (%), and Y_C is the solid residue yield (%). The estimated non-condensable gas yield was calculated by mass balance because gaseous products were not collected directly during the experiments.

Fuel Conversion Efficiency (FCE)

Fuel conversion efficiency (FCE) was used to evaluate the effectiveness of converting plastic feedstock into liquid fuel. The FCE was calculated as the ratio of the mass of liquid fuel produced to the initial feedstock mass using Equation (5) [8, 10].

$$FCE(\%) = \frac{W_o}{W_f} \times 100 \quad (5)$$

where W_o is the mass of the collected liquid fuel (kg) and W_f is the initial feedstock mass (kg). All calculated values are reported as the mean $\pm$ standard deviation of three independent experiments ($n = 3$).

Reactor Operational Performance

The operational performance of the developed reactor was evaluated using the maximum reactor temperature, time to first liquid fuel production, time to first combustible gas generation, total operating time, and heating-fuel consumption recorded during each experimental run. Reactor temperature was monitored continuously using the installed temperature gauge, while the onset times of liquid fuel and combustible gas production were recorded from the beginning of heating. Operational stability was assessed based on continuous vapor generation, uninterrupted cooling-water circulation, effective liquid condensation, and the absence of visible vapor leakage throughout the pyrolysis process. Waste lubricating oil consumption was determined from the difference between the initial and remaining fuel volumes in the supply tank after each run. Specific heating-fuel consumption was calculated using Equation (6):

$$\text{Specific fuel consumption (L kg}^{-1}\text{)} = \frac{V_h}{W_f} \quad (6)$$

where V_h is the volume of waste lubricating oil consumed during the experimental run (L), and W_f is the initial mass of plastic feedstock (kg). All operational parameters were determined separately for each run and are reported as the mean $\pm$ standard deviation of three independent experiments ($n = 3$).

Fuel Characterization, Blending, and Practical Utilization

Physicochemical Characterization of Pyrolysis Oil

The physicochemical properties of the produced pyrolysis oil were determined to evaluate its potential as an alternative transportation fuel. Prior to analysis, the collected oil was filtered through a 0.45- μm membrane filter to remove suspended particles and stored in airtight amber-glass bottles at room temperature. The higher heating value (HHV) was determined according to ASTM D240 using an

IKA C6000 bomb calorimeter (IKA-Werke GmbH & Co. KG, Staufen, Germany) at the Energy Physics Laboratory, Science and Technology Center, Loei Rajabhat University, Thailand. The calorimeter was calibrated with certified benzoic acid before each measurement in accordance with the manufacturer's operating instructions. Fuel density was determined according to ASTM D4052 at ambient temperature. The measured density was subsequently used to convert the collected liquid volume into mass for engineering performance calculations. All analyses were performed in triplicate, and the results are expressed as the mean $\pm$ standard deviation (SD).

Preparation of Fuel Blends

Preparation for improving the quality of pyrolysis oil produced for use as an alternative fuel in the agricultural sector, to enhance suitability and reliability for farming, involved blending the resulting oil with commercial gasoline and diesel in different volume ratios. Six blended fuel formulas were prepared, along with three control fuel formulas, as follows:

- Formula A: Pyrolysis oil : Gasoline = 1.0:1.0 (v v^{-1})
- Formula B: Pyrolysis oil : Gasoline = 0.5:1.0 (v v^{-1})
- Formula C: Pyrolysis oil : Gasoline = 1.0:0.5 (v v^{-1})
- Formula D: Pyrolysis oil : Diesel = 1.0:1.0 (v v^{-1})
- Formula E: Pyrolysis oil : Diesel = 0.5:1.0 (v v^{-1})
- Formula F: Pyrolysis oil : Diesel = 1.0:0.5 (v v^{-1})

The control fuels consisted of pure pyrolysis oil, commercial gasoline, and commercial diesel fuel. Each formulation was prepared by measuring the required fuel volumes using calibrated glass cylinders and mixing thoroughly at room temperature until a homogeneous blend was obtained. The prepared fuel blends were subsequently analyzed for density and higher heating value before practical utilization.

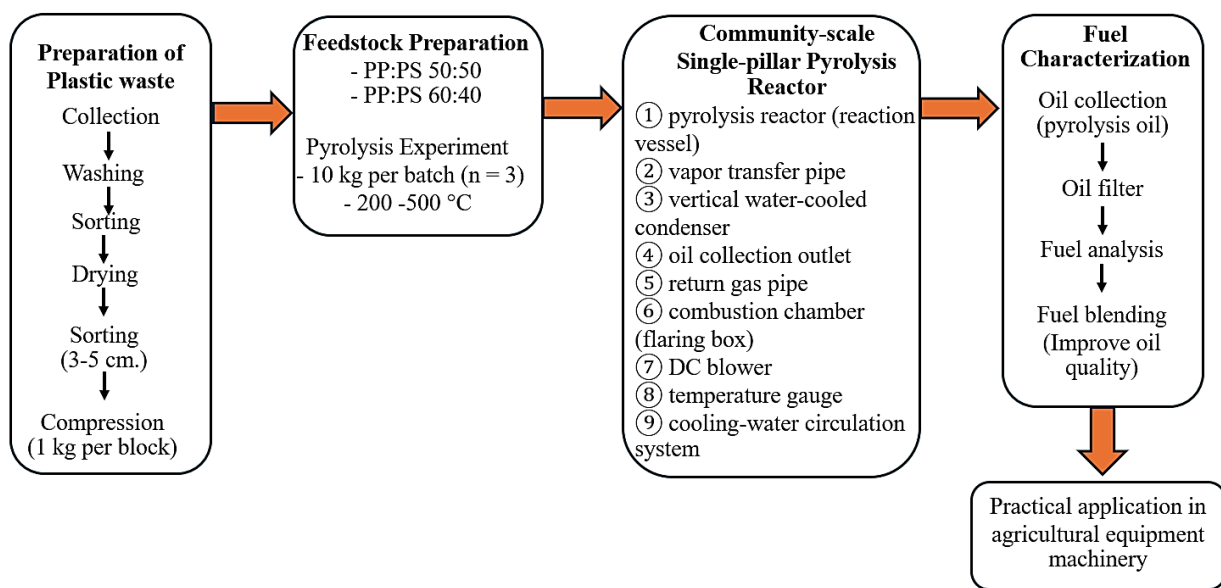


Fig. 3 Feedstock preparation and experimental design for the community-scale single-pillar pyrolysis study.

Practical Utilization Test

The practical applicability of the prepared fuel blends was evaluated under field conditions using gasoline-engine and diesel-engine agricultural machinery commonly used in rural communities. Gasoline blends were tested in a lawn mower and a portable irrigation water pump, whereas diesel blends were evaluated using a walking tractor and a four-wheel-drive agricultural utility vehicle. Before each test, the fuel system of each machine was drained and flushed to minimize contamination from residual fuel. Each blend was then tested under normal operating conditions and evaluated

for engine startability, operational stability, throttle response, continuous operation, visible exhaust smoke, abnormal engine noise, and successful completion of the assigned agricultural task. Commercial gasoline and diesel served as reference fuels. The objective of the field evaluation was to verify the practical applicability of the pyrolysis-derived fuel under real operating conditions rather than to conduct standardized engine performance certification. Therefore, engine power, brake-specific fuel consumption, combustion characteristics, and exhaust emissions were not measured.

Table 2 Experimental operating conditions of the community-scale single-pillar pyrolysis reactor.

Parameter	Specification
Feedstock	Non-recyclable polypropylene (PP) and polystyrene (PS)
Feedstock preparation	Washing, air drying (24 h), manual cutting (3 – 5 cm)
Feedstock block	1 kg per block
Feedstock composition	PP:PS = 50:50 and 60:40 (w w ⁻¹)
Batch capacity	10 kg per batch
Reactor type	Community-scale single-pillar batch reactor
Heating method	External combustion
Heating fuel	Waste lubricating oil
Catalyst	None
Carrier gas	None
Condensation	Vertical water-cooled condenser
Operating temperature	200 – 500 °C
Pressure	Atmospheric pressure
Replication	Three independent runs (n = 3) per treatment
Experimental design	Completely randomized design (CRD)
Statistical analysis	Welch's t-test ($\alpha = 0.05$)

Statistical Analysis

All experiments were conducted in triplicate, and the results are expressed as the mean $\pm$ standard deviation (SD). Statistical analyses were performed using IBM SPSS Statistics for Windows, Version 29.0 (IBM Corp., Armonk, NY, USA). Differences between the two feedstock compositions were evaluated using Welch's t-test because unequal variances between groups were assumed. Statistical significance was accepted at $p < 0.05$.

Community-Scale Field Validation and Technology Transfer

The developed single-pillar pyrolysis technology was transferred to practice through a Memorandum of Understanding (MOU) involving Loei Rajabhat University, local administrative organizations, schools, and 19 surrounding communities Appendix A (Fig. A1). Technology transfer included reactor operation, feedstock preparation, safety procedures, and utilization of pyrolysis-derived liquid fuel. The prototype was subsequently implemented under community conditions to validate its operational feasibility and suitability for decentralized plastic waste management and community-scale alternative fuel production.

3. Results and Discussion

Composition of Community Plastic Waste Feedstock

The composition of plastic waste collected from communities in Loei Province is presented in Fig. 4. Five major polymer types were identified, comprising polypropylene (PP), polystyrene (PS), polyethylene (PE), high-density polyethylene (HDPE), and low-density polyethylene (LDPE). This analysis was performed to identify representative feedstocks for the subsequent pyrolysis experiments. As shown in Fig. 4, PP was the dominant fraction ($41.25 \pm 2.31\%$), followed by PS ($31.28 \pm 1.84\%$), PE ($16.92 \pm 1.26\%$), HDPE ($9.00 \pm 0.95\%$), and LDPE ($1.55 \pm 0.32\%$). Together, PP and PS accounted for approximately 72.53% of the total plastic waste, indicating that these polymers represent the principal feedstocks available in the surveyed communities and are well suited for pyrolysis-based energy recovery. Their predominance is attributed to the widespread use of disposable food packaging, drinking cups, food containers, plastic lids, household packaging, and other consumer products. Similar distributions have been reported in municipal solid waste characterization studies, where PP and PS consistently constitute the major fractions of post-consumer plastic waste

because of their extensive use in packaging and food-service applications [1 – 3].

The high proportion of PP and PS provides a favorable feedstock for thermochemical conversion because both polymers are rich in hydrocarbons and contain relatively low oxygen levels, enabling efficient thermal decomposition into condensable hydrocarbons with high calorific values and relatively low char production. Previous studies have shown that PP generally produces high liquid-fuel yields because of its long aliphatic hydrocarbon chains, whereas PS enhances fuel quality through its aromatic structure and higher heating value [7, 8, 10]. Accordingly, PP and PS were selected as the primary feedstocks for reactor performance evaluation.

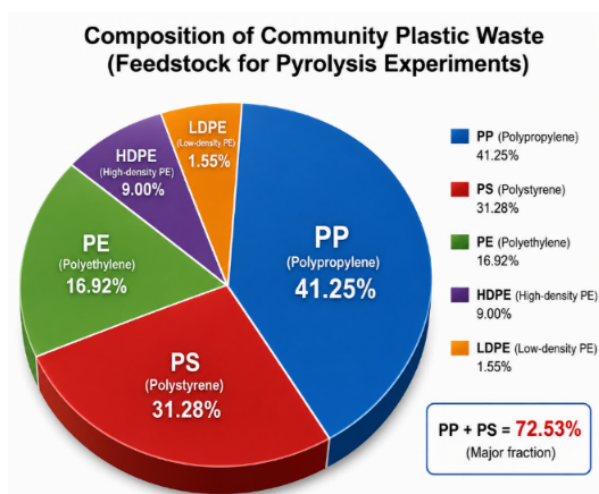


Fig. 4 Composition of community plastic waste used as feedstock for the pyrolysis experiments.

This selection reflects the actual waste composition of the study area and enhances the practical applicability of the proposed single-pillar reactor for decentralized community-scale plastic waste management. Furthermore, the feedstock selection strategy supports a localized circular economy by utilizing the dominant plastic fractions generated within participating communities rather than laboratory-prepared materials [19, 24].

Engineering Performance of the Developed Reactor

The engineering performance of the developed single-pillar pyrolysis reactor was evaluated using mixed polypropylene (PP) and polystyrene (PS) feedstocks under batch operating conditions. Two feedstock compositions, designated as R50 (PP:PS = 50:50) and R60 (PP:PS = 60:40), were investigated to evaluate reactor performance, product distribution, and fuel production efficiency. The reactor operated continuously and stably throughout all experimental runs without operational interruption or equipment failure, demonstrating its suitability for decentralized community-scale applications. The engineering performance parameters are summarized in Table 4.

Reactor Thermal Performance

The thermal performance of the developed single-pillar pyrolysis reactor was evaluated based on the maximum reactor temperature, time to first oil production, and total operating time. As summarized in Table 4, the maximum reactor temperature reached 341.67 ± 10.41 °C for the PP:PS (50:50) feedstock and 353.33 ± 5.77 °C for the PP:PS (60:40) feedstock, with no significant difference ($p > 0.05$). Similarly, the time to first oil production (56.67 – 60.00 min) and total operating time (190 – 200 min) were statistically comparable between the two feedstock compositions. The stable thermal performance observed in both experiments indicates efficient heat transfer and uniform thermal decomposition of the mixed plastic feedstocks. The reactor temperatures obtained (approximately 340 – 353 °C) fall within the optimum range reported for plastic pyrolysis, allowing efficient liquid fuel production while minimizing secondary cracking reactions [7, 8, 10].

Product Distribution

The distribution of pyrolysis products obtained from the two PP–PS feedstock compositions are presented in Table 4. Liquid fuel was the major product in both experiments, accounting for 65.33 ± 1.26 wt.% for the PP:PS (50:50) feedstock and 67.00 ± 1.91 wt.% for the PP:PS (60:40) feedstock. The corresponding oil volumes were 8.03 ± 0.21 and 8.27 ± 0.25 L per batch, respectively, with no statistically significant difference ($p > 0.05$). The solid residue represented only 8.93 – 9.27 wt.%, whereas the estimated gas yield ranged from 23.73 to 25.73 wt.%, indicating efficient conversion of mixed plastic feedstocks into condensable hydrocarbons. The overall product distribution was comparable between the two feedstock compositions, suggesting that slight variations in the PP:PS mixing ratio had little influence on reactor performance. Similar product distributions have been reported for the pyrolysis of mixed polyolefin plastics under comparable operating temperatures, where liquid fuel is the dominant product followed by non-condensable gases and solid residues [7, 8, 10].

Plastic Reduction Efficiency and Fuel Conversion Efficiency

The plastic reduction efficiency (PRE) and fuel conversion efficiency (FCE) of the developed single-pillar pyrolysis reactor are presented in Table 3. The reactor achieved PRE values of $91.07 \pm 0.40\%$ and $90.73 \pm 0.25\%$ for the PP:PS (50:50) and PP:PS (60:40) feedstocks, respectively, with no significant difference ($p > 0.05$). Likewise, the FCE values ranged from $71.74 \pm 1.27\%$ to $73.85 \pm 2.31\%$, indicating consistent conversion performance under both feedstock compositions. The high PRE values indicate that more than 90% of the plastic feedstock was thermally converted into useful products, while the FCE values demonstrate efficient production of liquid fuel. The absence of significant differences between the two feedstock ratios suggests that the developed reactor maintained stable conversion efficiency regardless of slight variations in PP and

PS composition. These results are consistent with previous studies reporting that stable operating temperatures of approximately 330 – 360 °C promote efficient thermal cracking and high fuel conversion during plastic pyrolysis [7, 8, 10].

Overall Engineering Performance Evaluation

The developed single-pillar pyrolysis reactor exhibited stable operation and efficiently converted mixed plastic waste into liquid fuel. Under both feedstock compositions, the reactor achieved maximum operating temperatures of 341.67 – 353.33 °C, liquid fuel yields of 65.33 – 67.00 wt.%, plastic reduction efficiencies exceeding 90%, and fuel conversion efficiencies above 71% (Table 3). No statistically significant differences ($p > 0.05$) were observed between the PP:PS 50:50 and 60:40 feedstocks, confirming consistent and reproducible engineering performance.

Compared with previously reported batch pyrolysis systems, the proposed reactor produced comparable liquid fuel yields while maintaining a compact and simplified

configuration suitable for community-scale applications. Its single-pillar design promoted efficient heat transfer, effective vapor condensation, and reliable fuel recovery without the use of catalysts or complex process-control systems. These characteristics make the reactor a practical option for decentralized plastic waste management and local alternative fuel production, particularly in rural communities requiring low-cost and easy-to-operate technologies [7, 8, 10].

As summarized in Table 4, the developed single-pillar pyrolysis reactor exhibited engineering performance comparable to or better than previously reported batch pyrolysis systems. The reactor achieved an oil yield of 65.3 – 67.0 wt.%, PRE above 90%, and FCE up to 73.9% while operating at a relatively low temperature (342 – 353 °C) without the use of catalysts. In addition, its simple single-pillar configuration and community-scale applicability distinguish it from conventional laboratory-scale reactors, demonstrating its potential for decentralized plastic waste management and alternative fuel production.

Table 3 Engineering performance and product distribution of the developed single-pillar pyrolysis reactor using mixed polypropylene (PP) and polystyrene (PS) feedstocks.

Parameter	Unit	PP:PS (50:50)	PP:PS (60:40)	<i>p</i> -value
Reactor thermal performance				
Maximum reactor temperature	°C	341.67 ± 10.41	353.33 ± 5.77	0.184
Time to first oil production	min	60.00 ± 5.00	56.67 ± 5.77	0.493
Operating time	min	200.00 ± 10.00	190.00 ± 10.00	0.288
Product distribution				
Oil volume	L per batch	8.03 ± 0.21	8.27 ± 0.25	0.286
Oil mass	Kg per batch	6.53 ± 0.13	6.70 ± 0.19	0.285
Oil yield	wt. %	65.33 ± 1.26	67.00 ± 1.91	0.285
Solid yield	wt. %	8.93 ± 0.40	9.27 ± 0.25	0.304
Estimated gas yield	wt. %	25.73 ± 1.12	23.73 ± 2.16	0.250
Engineering performance				
Plastic reduction efficiency (PRE)	%	91.07 ± 0.40	90.73 ± 0.25	0.304
Fuel conversion efficiency (FCE)	%	71.74 ± 1.27	73.85 ± 2.31	0.250
Oil productivity	L h ⁻¹	3.46 ± 0.29	3.73 ± 0.23	0.271
Fuel properties				
Oil density	kg per L	0.78 ± 0.01	0.79 ± 0.02	0.313
Higher heating value (HHV)	MJ kg ⁻¹	45.33 ± 0.29	45.73 ± 0.23	0.134
Energy consumption				
Heating fuel consumption	Kg per batch	2.20 ± 0.70	2.40 ± 0.10	0.671
Specific fuel consumption	L per kg	0.22 ± 0.07	0.24 ± 0.01	0.671

Note: Values are presented as mean ± standard deviation ($n = 3$). Statistical significance was determined using Welch's *t*-test at $p < 0.05$.

Fuel Properties of Pyrolysis Oil

The fuel properties of the pyrolysis oil produced from mixed polypropylene (PP) and polystyrene (PS) feedstocks are presented in Table 4. The oil exhibited densities of 0.78 ± 0.01 and 0.79 ± 0.02 kg L⁻¹ for the PP:PS (50:50) and PP:PS (60:40) feedstocks, respectively, with no significant difference ($p > 0.05$). Likewise, the higher heating value (HHV) ranged from 45.33 ± 0.29 to 45.73 ± 0.23 MJ kg⁻¹,

indicating a high energy content suitable for fuel applications. The comparable density (*D*) and HHV values obtained from both feedstock compositions indicate that slight variations in the PP:PS ratio had minimal influence on fuel quality. The HHV values are close to those reported for commercial diesel fuel and previously published plastic-derived pyrolysis oils, demonstrating the potential of the produced oil as an alternative fuel or blending component

for conventional fuels [7 – 10]. The produced pyrolysis oil was blended with commercial gasoline and diesel fuels at different volumetric ratios to assess its suitability as a transportation fuel, and the resulting physicochemical properties are summarized in Table 5.

Table 4 Comparison of the proposed single-pillar pyrolysis reactor with representative batch plastic pyrolysis systems.

Parameter	This study	Reported range	Reference
Reactor type	Single-pillar	Fixed-bed per Batch	[7 – 10]
Operating temperature (°C)	342 – 353	350 – 500	[7 – 10]
Oil yield (wt.%)	65.3 – 67.0	55 – 75	[7 – 10, 26]
PRE (%)	90.7 – 91.1	80 – 92	[8, 10, 26]
FCE (%)	71.7 – 73.9	60 – 75	[7, 8, 10, 26]
Catalyst	None	Usually required	[7, 8, 26]
Application	Community scale	Per Optional Laboratory per Pilot	[7 – 10, 26]

Table 5 Physicochemical properties of pyrolysis oil, blended fuels, and commercial fuels.

Fuel sample per Blend ratio (v v ⁻¹)	HHV (MJ kg ⁻¹)	D (g cm ⁻³)
Formula A Pyrolysis oil:Gasoline (1.0:1.0)	39.82 ± 0.34	0.70 ± 0.05
Formula B Pyrolysis oil:Gasoline (0.5:1.0)	42.02 ± 0.68	0.68 ± 0.01
Formula C Pyrolysis oil:Gasoline (1.0:0.5)	45.09 ± 0.17	0.70 ± 0.02
Formula D Pyrolysis oil:Diesel (1.0:1.0)	45.18 ± 0.71	0.78 ± 0.01
Formula E Pyrolysis oil:Diesel (0.5:1.0)	45.88 ± 0.46	0.80 ± 0.01
Formula F Pyrolysis oil:Diesel (1.0:0.5)	44.88 ± 0.14	0.79 ± 0.01
Pure pyrolysis oil (Control)	45.55 ± 0.04	0.78 ± 0.02
Commercial gasoline (Control)	40.40 ± 0.96	0.66 ± 0.01
Commercial diesel (Control)	44.83 ± 0.56	0.81 ± 0.08

The blending ratio influenced both the HHV and density of the fuel formulations. Among the diesel blends,

Formula E (pyrolysis oil : diesel = 0.5:1.0, v v⁻¹) exhibited the highest HHV (45.88 ± 0.46 MJ kg⁻¹) and a density (0.80 ± 0.01 g cm⁻³) close to commercial diesel fuel, whereas gasoline blends generally exhibited lower HHVs. These results indicate that blending with diesel improved fuel compatibility while maintaining a high energy content, supporting the subsequent practical utilization tests described in Section 3.4 [7, 8, 26].

Practical Utilization of Pyrolysis Fuel Blends

The practical applicability of the recovered pyrolysis oil was evaluated by blending it with commercial gasoline and diesel fuels and testing the blends in agricultural equipment (Fig. A1). Gasoline blends were successfully used in a lawn mower and a portable water pump, whereas diesel blends were tested in a walking tractor and an agricultural utility vehicle. All engines exhibited satisfactory startability and stable operation without abnormal vibration or excessive exhaust smoke. Gasoline engines operated successfully with a 1:1 (v v⁻¹) pyrolysis oil-gasoline blend, while diesel engines performed satisfactorily with blends containing 1 part pyrolysis oil to 0.5 parts diesel fuel or higher. These results agree with previous studies demonstrating that plastic-derived pyrolysis oils can be used as supplementary fuels after appropriate blending [27 – 29]. From a practical perspective, the proposed reactor enables locally available plastic waste to be converted into alternative liquid fuel, reducing both petroleum consumption and plastic waste disposal. Based on the estimated production cost and blending ratios, fuel expenditure could be reduced by approximately 50 – 75%. These findings demonstrate the potential of the proposed reactor as a decentralized waste-to-energy technology supporting community energy security and circular economic implementation.

Economic Feasibility and Community-Scale Validation Cost-Benefit Analysis of Pyrolysis Oil Production

A preliminary cost-benefit analysis was conducted to evaluate the economic feasibility of the developed community-scale pyrolysis reactor. As summarized in Table 6, the production cost of pyrolysis oil was estimated at 7.0 THB per L, including plastic feedstock preparation (3.0 THB per kg), heating fuel (0.5 THB per L), and labor and operating expenses (3.5 THB per L). During the study period, the average retail prices of commercial gasoline and diesel fuel were approximately 49.0 and 40.0 THB per L, respectively. Blending pyrolysis oil with commercial fuels further improved its economic competitiveness. A 1:1 (v v⁻¹) blend with gasoline reduced the fuel cost to 28.0 THB per L, representing a cost reduction of 42.9% compared with gasoline alone. Likewise, blending pyrolysis oil with diesel at a ratio of 1.0:0.5 (v v⁻¹) resulted in a fuel cost of 18.0 THB per L, corresponding to a 55.0% reduction relative to commercial diesel. Overall, the results demonstrate that the developed single-pillar pyrolysis reactor is both technically effective and economically feasible for community-scale applications. In addition to converting plastic waste into a value-added fuel, the system substantially reduces fuel costs

and provides an alternative energy source using locally available plastic waste. These advantages support decentralized plastic waste management, promote circular economic implementation, and enhance the long-term sustainability of rural communities.

Community-Scale Field Validation of the Developed Reactor

Community-scale field validation was conducted in 19 local communities in Mueang Loei District, Loei Province, Thailand, to verify the practical applicability of the proposed reactor. Following technology transfer and hands-on training, each community received one single-pillar

pyrolysis reactor and operated it under standardized conditions as shown in Fig. A2. Each unit processed 30 kg per day of mixed polypropylene (PP) and polystyrene (PS) waste (60:40, w w⁻¹) over a 30-day evaluation period. Reactor performance and product yields were continuously monitored, and the results are summarized in Appendix A (Table A2). Throughout the evaluation, all units operated reliably without major operational or safety issues. The average plastic reduction efficiency reached $92.96 \pm 0.87\%$, while accumulated community plastic waste was reduced by $55.51 \pm 22.41\%$. Daily pyrolysis oil production ranged from 20.5 to 25.0 L per day, depending on feedstock quality.

Table 6 Cost comparison of pyrolysis oil, blended fuels, and commercial fuels.⁸

Fuel type	Blend ratio (v v ⁻¹)	Estimated cost (THB per L)	Cost reduction (%)
Commercial gasoline	–	49.0	–
Commercial diesel	–	40.0	–
Pyrolysis oil	–	7.0	85.7
Pyrolysis oil + Gasoline	1.0:1.0	28.0	42.9
Pyrolysis oil + Diesel	1.0:0.5	18.0	55.0

Note: Production costs were estimated based on plastic feedstock, heating fuel, and operating expenses. Blended fuel costs were calculated according to the blending ratios used in this study. Capital investment, equipment depreciation, electricity, and distribution costs were excluded.

The recovered fuel was successfully utilized in agricultural machinery and donated to local crematoriums, demonstrating the technical feasibility and practical value of the proposed system for decentralized community-based plastic waste management. These findings confirm that the developed single-pillar pyrolysis reactor can be successfully implemented under real community operating conditions while maintaining stable engineering performance and high plastic conversion efficiency. The combination of technology transfer, local participation, and practical fuel utilization demonstrates the potential of this system as a decentralized solution for plastic waste management, renewable energy production, and circular economic implementation in rural communities

4. Conclusion

This study successfully developed and validated an innovative single-pillar community-scale pyrolysis reactor for converting mixed polypropylene (PP) and polystyrene (PS) plastic waste into alternative liquid fuel. The developed reactor demonstrated stable engineering performance under optimum operating conditions, achieving a liquid fuel yield of 65.33 – 67.00 wt.%, a plastic reduction efficiency (PRE) exceeding 90%, and a fuel conversion efficiency (FCE) of 71.74 – 73.85%. The produced pyrolysis oil exhibited favorable fuel characteristics, including a density of 0.78 – 0.79 kg L⁻¹ and a higher heating value of 45.33 – 45.73 MJ kg⁻¹, indicating its suitability as an alternative fuel for agricultural machinery and other small-scale applications. In addition, the preliminary economic assessment demonstrated that pyrolysis oil could be produced at an estimated cost of approximately 7 THB per L, while optimized blended fuels reduced fuel costs by

approximately 50 – 75% compared with commercial fuels. A major contribution of this research is the successful integration of reactor development, engineering performance evaluation, economic assessment, and community-scale field validation within a single study. Unlike most previous plastic pyrolysis studies that remain at laboratory or pilot scales, the proposed reactor was successfully deployed in 19 local communities, where it achieved an average PRE of $92.96 \pm 0.87\%$ under actual operating conditions. These results demonstrate that the developed technology is technically reliable, economically feasible, and readily transferable to local communities for decentralized plastic waste management.

Beyond its engineering performance, the proposed reactor supports Thailand's Bio-Circular-Green (BCG) Economy by converting plastic waste into value-added energy while contributing to SDGs 7, 11, 12, and 13 through decentralized waste management, resource recovery, and greenhouse gas reduction [30, 31]. Future research should focus on long-term engine durability, exhaust emissions, life-cycle assessment, and large-scale techno-economic evaluation. Overall, the developed single-pillar pyrolysis reactor provides practical, low-cost, and scalable technology for sustainable community-based plastic waste management and renewable energy production.

5. Suggestions

Future research should focus on optimizing reactor operating conditions, improving fuel quality, and evaluating long-term engine performance and exhaust emissions. In addition, comprehensive techno-economic and life-cycle assessments are recommended to support large-scale community implementation.

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7. Declaration of Generative AI in Scientific Writing

The authors declared that generative AI tools were used solely to improve the clarity of the language, grammar, and formatting of this manuscript. No content, data interpretation, or research findings were generated or modified by AI.

8. CRediT Author Statement

Vanlop Thathong: Conceptualization, Data curation, Methodology, Investigation, Validation, Writing – Review & Editing, Project Administration. **Tanunchai Boonnuk:** Software, Data Curation, Formal Analysis, Visualization. **Netnapid Tantamsapya:** Resources, Supervision, Data Curation, Validation, Review & Editing. **Nuwut Phimpabut:** Conceptualization, Methodology, Formal Analysis, Data Curation, Writing – Original Draft, Writing – Review & Editing, Supervision, Project Administration. All co-authors have read and approved the final manuscript.

9. Research Involving Human and Animals Rights

Not applicable

10. Ethics Approval and Consent to Participate

Not applicable

11. Declaration of Competing Interest

The authors declare that they have no competing interests

12. References

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Appendix A. supplementary engineering information



Fig. A1 Practical application in (a) diesel-powered agricultural and (b) gasoline-powered agricultural equipment machinery



Fig. A2 Technology transfer and community-scale implementation of the developed single-pillar pyrolysis reactor. (a) Memorandum of Understanding (MOU) with local stakeholders. (b) Training in plastic waste management and pyrolysis technology. (c) Hands-on reactor operation. (d) Reactor installation and demonstration. (e–g) Community-scale deployment in Loei Province, Thailand.

Table A1 Distinguishing features of the proposed single-pillar pyrolysis system relative to commonly reported plastic-pyrolysis approaches.

Comparison criterion	Commonly reported approaches	Present study
Research emphasis	Optimization of operating conditions, product yield, or fuel properties	Integration of reactor development, engineering evaluation, and community-scale field validation
Reactor concept	Conventional fixed-bed, fluidized-bed, rotary-kiln, auger, or other laboratory per pilot configurations	Locally fabricated single-pillar batch reactor with an integrated vertical water-cooled condenser
Operating mode	Batch or continuous operation, depending on reactor design	Simplified batch operation suitable for decentralized use
Heat supply	Electricity, conventional fuels, or externally supplied process heat	External combustion using waste lubricating oil
Catalyst requirement	Thermal or catalyst-assisted operation	Catalyst-free thermal conversion
Feedstock	Frequently controlled, single-polymer, or model plastic feedstocks	Non-recyclable PP and PS mixtures representative of locally available plastic waste
Engineering evaluation	Commonly focused on product yield and selected fuel properties	Product distribution, PRE, FCE, heating-fuel consumption, oil productivity, residual solids, mass balance, HHV, and density
Experimental verification	Laboratory or pilot testing, with varying levels of replication	Replicated experiments and statistical comparison of selected feedstock conditions
Technology transfer	Infrequently integrated into reactor-performance studies	Operator training and reactor implementation in local communities
Field validation	Usually limited or conducted at a single experimental site	Practical operation and validation across 19 community sites
End-use assessment	Laboratory characterization or controlled engine testing	Practical use of recovered fuel in selected agricultural and community equipment
Principal contribution	Process or product optimization under controlled conditions	Integration of simplified reactor engineering with practical fuel utilization and multi-site community implementation

Table A2 Community-scale field validation of the developed single-pillar pyrolysis reactor in 19 local communities in Mueang Loei District, Thailand.

Community	Oil production (L day ⁻¹)	Solid residue (kg day ⁻¹)	PRE (%)	Plastic waste collected (kg day ⁻¹)	Plastic reduction (%)	Utilization of pyrolysis oil
Loei Municipality	24.5	2.73	90.90	150	20.00	Crematorium fuel
Na-or Municipality	23.5	2.54	91.53	80	37.50	Crematorium fuel; Agricultural engines
Na-an Municipality	20.5	2.35	92.17	55	54.55	Crematorium fuel; Agricultural engines
Na-pong Municipality	22.5	2.54	91.53	70	42.86	Crematorium fuel; Agricultural engines
Na-din-dam Municipality	23.5	2.05	93.17	65	46.15	Crematorium fuel; Agricultural engines
Nam-suai Municipality	24.0	1.98	93.40	60	50.00	Crematorium fuel; Agricultural engines
Mueang SAO	24.5	2.00	93.33	80	37.50	Crematorium fuel; Agricultural engines
Na-khaem SAO	23.0	2.15	92.83	65	46.15	Crematorium fuel; Agricultural engines
Kok-du SAO	21.5	1.85	93.83	50	60.00	Crematorium fuel; Agricultural engines
Kok-thong SAO	20.5	1.85	93.83	50	60.00	Crematorium fuel; Agricultural engines
Chaiyapruet SAO	25.0	2.00	93.33	60	50.00	Crematorium fuel; Agricultural engines
Nam-man SAO	24.0	2.30	92.33	50	60.00	Crematorium fuel; Agricultural engines
Si Song Rak SAO	20.5	2.10	93.00	60	50.00	Crematorium fuel; Agricultural engines
Nam-suai SAO	21.5	1.95	93.50	60	50.00	Crematorium fuel; Agricultural engines
Siao SAO	23.5	2.05	93.17	50	60.00	Crematorium fuel; Agricultural engines
Mueang Loei District Office	24.5	1.85	93.83	30	100.00	Crematorium fuel
Ban Kamnoet Phet Community	20.5	2.00	93.33	30	100.00	Crematorium fuel; Agricultural engines
Loei Anukulwittaya School	23.5	2.00	93.33	30	100.00	Brush cutter
Loei Rajabhat University	25.0	1.85	93.83	100	30.00	Crematorium fuel; Agricultural engines
Mean ± SD	22.97 ± 1.61	2.12 ± 0.25	92.96 ± 0.87	55.79 ± 29.95	55.51 ± 22.41	

Note: PRE = Plastic reduction efficiency; SAO = Subdistrict Administrative Organization (Thailand).