

Evaluating Techno-Economic and Environmental Feasibility of Plastic Waste Pyrolysis under Malaysia Market: A Process Simulation Approach

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Abstract

Rapid plastic consumption has led to significant plastic waste accumulation. In Malaysia, where recycling rates remain low, alternative waste-to-resource pathways are needed to complement conventional practices. Among these technologies, plastic waste pyrolysis offers a promising route to convert mixed plastic waste into value-added products. However, comprehensive studies integrating process modelling and simulation, techno-economic evaluation, and environmental assessment under Malaysian market conditions remain limited. This work develops an integrated process modelling and simulation framework to evaluate the feasibility of pyrolyzing mixed plastic waste. The framework combines market analysis, site selection, steady-state process simulation, techno-economic analysis, and environmental assessment to establish a comprehensive desktop evaluation methodology. Aspen Plus V14 was used to develop the process flowsheet and generate mass and energy balances. The proposed process was designed to treat 6850 kg/h of plastic waste, producing 68.5% pyrolysis plastic oil, 3.6% char, and 27.8% fuel gas. Site selection analysis identified Klang, Selangor, as the most suitable location due to its robust recycling network, Port Klang logistics, and utility access. Economic evaluation indicates a positive Net Present Value and acceptable payout period under subsidized feedstock scenarios, with strong sensitivity to feedstock price. Environmental assessment based on Scope 1 and 2 greenhouse gas shows that direct emissions from on-site fuel combustion are the primary contributor to CO₂-equivalent (CO₂e) emissions. Utilization of internally generated fuel gas for process heating reduces total operating expenditure by 4.6%, shortens the payout period by 18.7%, and lowers overall CO₂e emissions by 10.7%, with minimal impact on capital cost.

Keywords

pyrolysis, plastic waste, Aspen Plus

1 Introduction

Plastic waste (PW) has become one of the most challenging global environmental issues. The rapid increase in plastic production and usage, reaching approximately 400 million tons annually, has led to a significant increase in plastic waste [1]. Around half of all plastic waste produced has been manufactured in just the last 15 years, reflecting the rapid growth in global plastic consumption and production. Globally, only 9% of plastic waste is recycled, 19% incinerated, 50% ends up in landfills, and the remaining 22% is inadequately managed [2]. According to Lai and Lee [3] worldwide plastic production is estimated to be around 1.1 billion tons by 2050,

with estimated global outputs ranging from 902 million tons to as high as 1,124 million tons. In addition, reports by the Environmental Protection Agency (EPA) indicate that only 7% of plastic waste generated annually is recycled, whereas approximately 8% is incinerated and the majority is landfilled [2]. Current plastic waste management practices remain heavily dependent on landfilling and incineration, both of which pose considerable risks to ecosystems, public health, and long-term environmental sustainability. These conventional approaches are increasingly viewed as unsustainable and are no longer reliable. In Malaysia, approximately 10.7 million tons of plastic

waste were generated in 2015 and ranked eighth among the top ten countries worldwide for mismanaged plastic waste [4]. Based on 2019 data, approximately 1.41 million tons/year of five key plastic resins, namely polyethylene terephthalate (PET), polypropylene (PP), low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), and high-density polyethylene (HDPE), were consumed [5]. Of this amount, only about 24% were recycled, while the remaining approximately 1.07 million tons remained unrecycled, which remains below Malaysia's national recycling target [5, 6]. This substantial unrecovered plastic waste highlights the urgent need for alternative waste valorization pathways beyond conventional mechanical recycling methods to support more effective waste management strategies and reduce the environmental impacts associated with plastic waste accumulation.

Among the wide range of thermochemical conversion through pyrolysis offers a more sustainable alternative due to its ability to reduce emissions and process various plastic waste streams with minimal preprocessing required. Pyrolysis reaction works by breaking down the polymer chains into smaller hydrocarbon compounds under high temperature conditions in an oxygen-free environment, producing valuable products [7]. The types of plastic waste used in pyrolysis process result in different oil yields. HDPE, LDPE and PP have higher oil yield potential while providing thermal stability, while PET and polyvinyl chloride (PVC) produce corrosive or toxic byproducts at high temperatures [7–9]. Despite its advantages, implementation of the pyrolysis process in industry with proper emission control and waste valorization strategy is very limited. While Malaysia stands to gain significantly from the widespread adoption of plastic waste pyrolysis, comprehensive studies that integrate process modelling and simulation, techno-economic evaluation, and environmental assessment within the context of Malaysian market conditions remain scarce.

Previous studies have provided important foundations for plastic waste pyrolysis modelling and techno-economic assessment in Malaysia. Sahu et al. [10] conducted an Aspen Plus simulation and feasibility study for catalytic cracking of waste plastics into fuel oil with reference to Malaysia, demonstrating the technical potential of plastic-to-fuel conversion. Nevertheless, their work mainly focused on catalytic cracking process simulation and preliminary feasibility, while a detailed techno-economic evaluation based on current Malaysian feedstock prices, product prices, subsidy assumptions, and site-specific

supply-chain conditions was not comprehensively addressed. Lim and Tan [11] evaluated the techno-economic feasibility of an organic and plastic waste pyrolysis pilot plant in Malaysia, demonstrating the potential of pilot-scale pyrolysis oil production using flue gas as the pyrolysis agent. However, their study focused on organic–plastic waste co-pyrolysis at pilot scale rather than an industrial-scale mixed polyolefin plastic waste system.

Recent process design and economic assessment studies have also advanced plastic waste pyrolysis modelling, yield prediction, and sensitivity analysis [12]. However, these studies generally rely on non-Malaysian market assumptions and therefore may not directly represent local feedstock availability, product prices, utility tariffs, subsidy schemes, and plant-location considerations. Thus, an integrated process simulation, techno-economic, and environmental evaluation of mixed plastic waste pyrolysis using Malaysia-specific market data, site-selection analysis, heat-utilization assessment, and feedstock-price sensitivity is still required. To address this gap, this study develops an integrated process modelling and simulation framework to assess the feasibility of converting mixed plastic waste in Malaysia through pyrolysis by incorporating market analysis, site selection, steady-state process simulation, techno-economic analysis, and environmental assessment.

1.1 Plastic waste sources and availability

Plastic waste can be categorized as post-industrial or post-consumer. Post-industrial waste includes offcuts and production scraps that have not reached the consumer market, while post-consumer waste consists of discarded plastics such as bottles and packaging diverted from landfills. By considering the plastics pyrolysis characteristics, this study focuses on HDPE, LDPE and PP due to their high oil yields and favorable pyrolysis performance, while PET and PVC were excluded because they generate corrosive or hazardous by-products under pyrolysis conditions [7]. Post-industrial waste is more expensive due to cleaner quality and consistent supply. The average market prices for these feedstocks are approximately RM 3.537/ton (HDPE), RM 3.595/ton (LDPE), and RM 3.861/ton (PP). Mixed or lower-grade post-consumer materials on the other hand are significantly cheaper but may require more preprocessing. Price from a supplier indicates a range between USD 350–400/ton (RM 1,470–1,680/ton) [13]. For economic viability of pyrolysis, a low-cost scenario with mixed feedstocks is preferable. Before processing, plastic waste should undergo pretreatment,

including sorting by type, cleaning to remove contaminants, and shredding to reduce size and increase surface area for pyrolysis. With over 30 active recyclers supplying pretreated resin pellets in Malaysia, this study utilized these readily available recycled plastics as feedstock. Table 1 lists some of the plastic recyclers in Malaysia of which most of them are located in the state of Selangor. According to a regional overview [14], Malaysia provides a support subsidy of USD 100–120/ton (RM 420–504/ton) of waste to pyrolysis plants, aimed at promoting standardized operations and encouraging investment in the sector.

1.2 Demand for pyrolysis products

Pyrolysis plastic oil (PPO) is produced through the thermal degradation of plastic polymers in the absence of oxygen, yielding C5-C20 hydrocarbon compounds suitable for fuel applications [15] and has different properties depending on their feedstock. Table 2 [16] compares the properties of pyrolysis plastic from plastic and tire waste with diesel properties while Table 3 compares the properties of PPO from different types of plastic waste with

Table 1 List of plastic recyclers in Malaysia

District & State	Company
Klang, Selangor	Asasrama, CY Intertrade, Galaxy Polymers, Zinco Colours Compounding, CY Plastic Recycling, Plastic V
Kapar, Selangor	JS Polymer Industry, Perusahaan Chew Hur, RS Polymer Industry
Telok Panglima Garang, Selangor	Megatrax Plastic Industries
Kajang, Selangor	MIS Plastic
Port Klang, Selangor	HKS Century
Puncak Alam, Selangor	Wit Polymer
Semenyih, Selangor	Danex Plastic
Shah Alam, Selangor	EPD Plastic Industries, Seri Alam Manufacturing
Ipoh, Perak	Ipoh S.Y Recycle Plastic
Teronoh, Perak	Sheng Foong Plastic Industries
Nilai, Negeri Sembilan	Diyoub Fibre (M)
Gadut, Negeri Sembilan	NS Plastic & Metal Trading
Senai, Johor	SG Green Resources
Ulu Tiram, Johor	Sunyjaya Plastic Industries
Pasir Gudang, Johor	Topflight Plastics
Kuala Lumpur	Spot Trend, Tritex Polymer, Wespac Waste Management
Bintulu, Sarawak	Kanma Plastic Material
Kota Kinabatangan, Sabah	Global Xess Int

Table 2 Properties of pyrolysis oil and diesel oil [16]

Property	Tire pyrolysis oil	PPO	Diesel
Heating value, kJ/kg	43226	46199	45815
Density, g/cm ³	0.924	0.815	0.799
Viscosity, mPa·s	2.69	2.49	1–4.11
Flash point, °C	68	100	70
C, %	84.57	83.79	87
H, %	10.44	11.36	13
O, %	4.17	2	–
Cl, %	–	0.03	–
S, %	≤1	–	–

Table 3 Properties of PPO from different plastic compared to diesel [15]

Property	PET	HDPE	PVC	LDPE	PP	PS	Diesel
Calorific value, MJ/kg	28.2	40.5	21.1	39.5	40.8	43.0	43.0
Density, g/cm ³	0.9	0.89	0.84	0.78	0.86	0.85	0.81
Kinematic viscosity, mm ² /s	-	5.08	6.36	5.56	4.09	1.4	1.9–4.1

diesel. The demand for pyrolysis oil is highly dependent on its intended applications. Some key applications include burning oil, utility boilers, cement kilns, furnaces oil, electricity generators and fuel oil. This various usage of pyrolysis oil makes it a versatile and valuable resource in multiple industries, driving its demand and potential for wider adoption. The global pyrolysis oil market was valued at USD 302.1 million (RM 1.27 billion) in 2020 and is projected to reach USD 459.3 million (RM 1.93 billion) by 2031, with a compound annual growth rate (CAGR) of approximately 4%.

In Malaysia, commercial plants using diverse feedstocks including oil palm waste, waste tires, and plastic waste. Due to its similar properties to fossil diesel, PPO can serve as an alternative fuel for boilers, furnaces, and generators. Comparative analyses show PPO has a calorific value of 40 MJ/kg, comparable to conventional diesel [15, 17]. The selling price for pyrolysis oil varies greatly depending on the source material and its chemical composition. Market reports estimate the Malaysia Pyrolysis Oil Market's revenue was USD 1.2 billion (RM 5.04 billion) in 2024, with global prices for pyrolysis oil ranging from approximately USD 560–665/metric ton

(RM 2,352–2,793/metric ton) as of early 2025 [18]. According to Lim and Tan [11] the selling price of pyrolysis oil locally is RM 0.60/kg. A higher export price can reach RM 1.36/kg for premium fuel-grade or bunker fuel quality. For economic analysis we assumed the global price of USD 560/metric ton as base case. Apart from PPO, char is also a byproduct of pyrolysis. It is rich in carbon and has low amounts of hydrogen, oxygen and minerals. The application includes catalyst, soil conditioner, heavy metal absorber, feed additive, biofuel and wastewater treatment, soil conditioner, heavy metal absorber, feed additive, biofuel and wastewater treatment.

The global market size for char in 2024 was reported to be USD 763.48 million (RM 3.21 billion) and expected to grow higher to USD 859.04 million (RM 3.61 billion) in 2025 and USD 2,097.72 million (RM 8.81 billion) in 2032. In Malaysia, char market size reached USD 0.2 million in 2022 (RM 0.84 million), and it is expected to increase to USD 0.7 million (RM 2.94 million) in 2030. The current price for char in Malaysia is around RM 0.80/kg [19].

1.3 Plant site selection

The selection of a plant location is a critical early-stage decision in chemical process design for the project's long-term technical viability and economic performance. According to Peters et al. [20], plant site selection involves interconnected technical, economic, logistical, social, and regulatory considerations. In this study, several key factors were evaluated to identify the most suitable location for the plastic pyrolysis plant, including feedstock availability, market access, energy supply, climate, transportation facilities, water supply, waste disposal facilities, labor supply, site characteristics, flood and fire protection, and community factors. Based on these criteria, a quantitative site selection matrix was developed using a simplified factor rating approach [21]. A three-point rating scale was adopted, where 3 represents the highest suitability, 2 indicates moderate suitability, and 1 denotes low suitability. Each site candidate was rated against each factor, and the cumulative scores were used to provide a quantitative basis for selecting the preferred plant location.

Three potential sites were shortlisted which were Klang (Selangor), Sungai Petani (Kedah) and Ipoh (Perak). Table 4 shows the selection factors and the rating for each candidate. Klang was selected as the location for the proposed plant with a total rating score of 27 followed by Sungai Petani (22) and Ipoh (21). Klang offers significant advantages, including a well-developed recycling

network supplying consistent HDPE, LDPE, and PP feedstock, proximity to major suppliers, and established logistics infrastructure through Port Klang and Kuala Lumpur International Airport (KLIA). Additionally, Klang provides reliable access to utilities, comprehensive waste management facilities, and a skilled labor force to support continuous operations. Although certain operational costs such as labor and water tariffs are higher compared to other sites, the strategic advantages of Klang make it the most practical and sustainable location for the pyrolysis plant.

2 Process description

Fig. 1 illustrates the process flow diagram of plastic waste pyrolysis system, which comprises four main processing stages namely drying, pyrolysis reaction, solid-gas separation, and product fractionation. A pre-processed mixed plastic waste is first introduced into a dryer operating above 100 °C, where residual moisture is removed through evaporation using hot process gas as the drying medium, producing a dried plastic feed and a water vapor overhead stream.

The dried feed is then conveyed to the pyrolysis reactor, which operates at approximately 500 °C under an oxygen-free environment to thermally decompose the plastic polymers producing vapor-solid product stream consisting of hydrocarbon, fuel gas, ash, and char. Process heat is supplied by a fired heater fuelled by external fuel and combustion air, providing the thermal duty required to sustain pyrolysis reactor temperature. A cyclone separator is used to remove 99.9% of solid ash and char particulates from the reactor product stream, after which the clarified gas is passed through a cooler to reduce the stream temperature suitable for downstream fractionation. The cooled vapor stream is then fed to an 18-stage distillation column, where non-condensable light hydrocarbons (<C6) are recovered as fuel gas from the overhead stream, while the bottom product consists of pyrolysis oil (PPO) containing hydrocarbons with carbon numbers $\geq$ C6.

3 Methodology

The methodological framework employed in this study integrates process modelling and simulation to evaluate the technical, economic, and environmental feasibility of mixed plastic waste pyrolysis. The framework is structured into several components which include process modelling and simulation, techno-economic evaluation, and environmental assessment. This integrated desktop-based approach ensures methodological consistency between process performance and the corresponding economic and

Table 4 Factors and rating of plant locations

No	Factors	Rating: (3) = highest, (2) = medium, (1) = lowest		
		Klang, Selangor	Sungai Petani, Kedah	Ipoh, Perak
1	Feedstock availability (# of supplier)	16 (3)	4 (2)	2 (1)
2	Existing market access (# of company)	4 (1)	1 (3)	2 (2)
3	Energy supply	Tenaga Nasional Berhad (3)	Tenaga Nasional Berhad (3)	Tenaga Nasional Berhad (3)
4	Climate	Average temperature of 25.4 °C and annual rainfall of 2000–2500 mm (1)	Average temperature of 25.4 °C and annual rainfall of 2000–2500 mm (1)	Average temperature of 25.4 °C and annual rainfall of 2000–2500 mm (1)
5	Transportation facilities	Road, Port Klang and KLIA (3)	Road, Penang Int. Airport (2)	Road, Ipoh Int. Airport (2)
6	Water supply	0–35 m ³ @ RM 2.62, >35 m ³ @ RM 2.86 (1)	0–20 m ³ @ RM 0.75, 21–35 m ³ @ RM 1.30, >35 m ³ @ RM 1.75 (3)	0–20 m ³ @ RM 0.75, 21–35 m ³ @ RM 1.08 (3)
7	Waste disposal facilities	176 licensed scheduled waste (SW) facilities (3)	51 licensed SW facility (1)	79 licensed SW facility (2)
8	Labor supply	Labor force rate: 76.4% (3)	Labor force rate: 66.8% (2)	Labor force rate: 65.8% (2)
9	Site characteristics	Average elevation: 13 m (3)	Average elevation: 45 m (2)	Average elevation: 205 m (1)
10	Flood and fire protection	5 fire stations (3)	1 fire station (1)	3 fire stations (2)
11	Community factors, i.e., living cost, transportation, healthcare and education	High (3)	Medium (2)	Medium (2)
Total rating score		27	22	21
Rank		1	2	3

The symbol "@" denotes the applicable water tariff for each consumption range. To avoid ambiguity, the notation has been revised using "at" and the tariff unit RM/m³. RM refers to Malaysian Ringgit, the currency of Malaysia.

environmental assessment, ensuring minimal manual data transfer errors and enabling systematic evaluation of process improvement scenarios. The following sections further elaborate on each component of the framework.

3.1 Process simulation

3.1.1 Feed specifications

In this work, Aspen Plus V14 was used to model and simulate the pyrolysis process. The feedstock was specified at 60,000 tons/y with feed flowrate of 6850 kg/h which comprises PP, LDPE, and HDPE. These types of plastic were chosen as it produces the highest amount of C and H, the lowest amount of O, least dangerous emissions and impurities, and the highest high heating value (HHV) [22]. To allow for fundamental analysis of plastic waste in Aspen Plus, the plastic mixtures were treated as a non-conventional (NC) solid component and subsequently

characterized based on their normalized proximate and ultimate analyses [23]. Table 5 shows the weighted and normalized proximate and ultimate analysis of plastic waste used in this work in a 50:25:25 ratio of PP, LDPE and HDPE respectively. The selected feedstock ratio was assumed based on the expected availability of these polymers in municipal plastic waste streams. PP was assigned the highest proportion due to its widespread use in packaging and consumer products and among the most recycled plastics in Malaysia [24]. Although the chosen ratio represents a conservative assumption, it provides a simplified representation of the dominant plastic waste fractions for the purposes of process simulation and techno-economic assessment in this study. Nevertheless, a comprehensive evaluation of varying plastic waste compositions and their influence on process performance is recommended for future investigations.

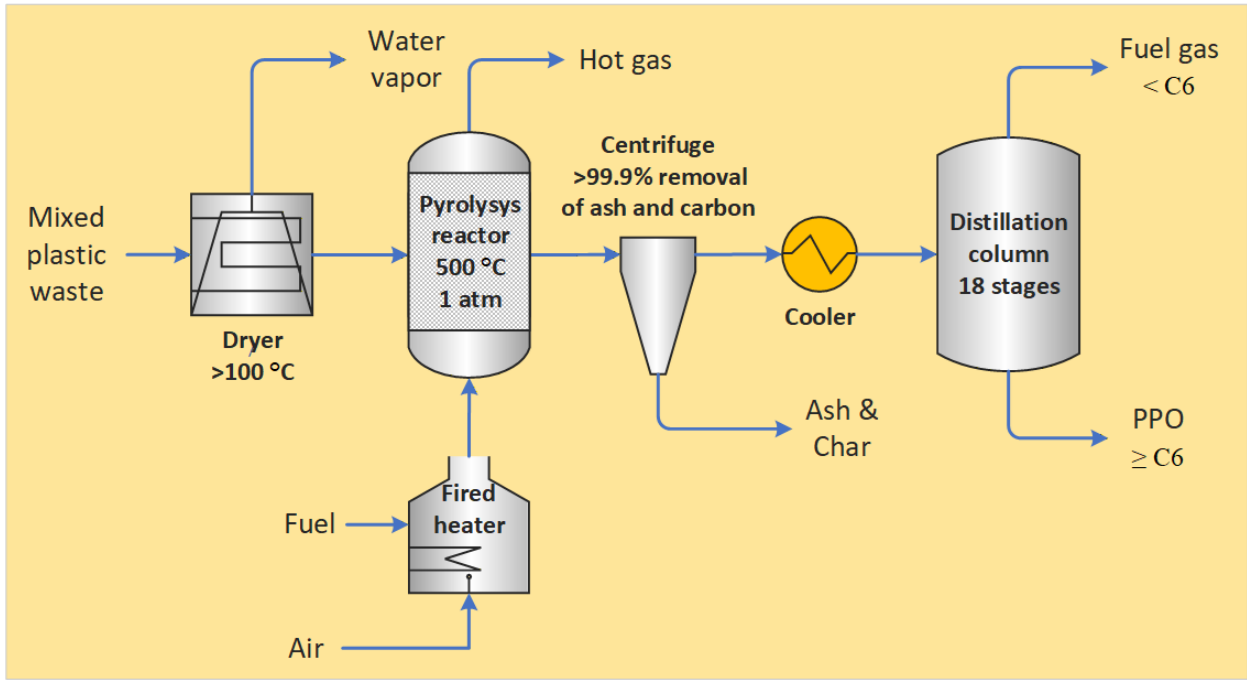


Fig. 1 Plastic waste pyrolysis process flow diagram

Table 5 Weighted and normalized proximate and ultimate analysis (wt.%) of mixed plastic waste used in this work at a PP:LDPE:HDPE mass ratio of 50:25:25

	PP	LDPE	HDPE	Normalized
Proximate				
- Moisture	0.15	0.17	0.04	0.13
- Ash	2.18	6.12	0.14	2.65
- Fixed carbon	0.21	0.60	0.22	0.31
- Volatile matter	97.61	93.28	99.64	97.91
Ultimate				
- Ash	6.12	0.14	2.66	2.59
- C	83.52	85.9	84.46	82.27
- H	14.50	13.79	14.01	13.64
- N	0.43	0.02	0.22	0.21
- O	1.56	0.30	1.32	1.29

3.1.2 Thermodynamic model

For this work, the Peng-Robinson Equation of State with Boston-Mathias (PR-BM) method was used to calculate the physical properties as well as phase equilibrium of pure components and mixtures [25]. The solid plastic waste was modeled in Aspen Plus as a non-conventional solid. The NC component models for enthalpy and density properties calculations were empirical correlations that require solid material characterization information derived from constituent ultimate and proximate analyses. The estimates were based on the general coal enthalpy model, including several correlations to compute the heat of combustion, heat of formation, and heat capacity.

In this work, the Boie correlation was used to calculate the heat of combustion on a dry, mineral-matter-free basis, $\Delta_c h_i^{dm}$, expressed in J/kg, according to Eq. (1):

$$\Delta_c h_i^{dm} = \left(a_{1i} w_{C,i}^{dm} + a_{2i} w_{H,i}^{dm} + a_{3i} w_{S,i}^{dm} \right) 10^2 + a_{6i} \quad (1)$$

$$+ a_{4i} w_{O,i}^{dm} + a_{5i} w_{N,i}^{dm}$$

where i refers to the non-conventional mixed-plastic component, w is the mass fraction of the constituent and the constant terms, a_{1i} to a_{5i} are empirical correlation coefficients representing the contributions of carbon, hydrogen, sulfur, oxygen, and nitrogen, respectively, to the heat of combustion, while a_{6i} is an empirical bias-correction constant derived from the IGT study [26]. Superscript dm indicates dry, mineral-matter-free basis. Products were in the form of ash, liquid water, and gaseous CO_2 , SO_2 , and NO_2 . The calculation of the heat of formation, $\Delta_f h_i^d$ was based on the standard heat of combustion-based correlation. The numerical coefficients, ω were combinations of stoichiometric coefficients and heat of formation for CO_2 , H_2O , HCl , and NO_2 at 25 °C represented by Eq. (2).

$$\Delta_f h_i^d = \Delta_c h_i^d - \left(\begin{aligned} &1.418 \times 10^6 \omega_{H,i}^d + 3.278 \times 10^5 \omega_{C,i}^d \\ &+ 9.264 \times 10^4 \omega_{S,i}^d - 2.418 \times 10^4 \omega_{N,i}^d \\ &- 1.426 \times 10^4 \omega_{Cl,i}^d \end{aligned} \right) 10^2 \quad (2)$$

where $\Delta_f h_i^d$ is the heat of formation expressed in J/kg on a dry basis. The heat capacity, $C_{p,i}^d$ calculations were based on Kirov correlations, which treat the heat capacity as a

weighted sum of the heat capacities of the constituents, that include moisture (*moist*), fixed carbon (FC), volatile matter (VM) and ash represented by Eq. (3) where w_j is the mass fraction of constituent j on a dry basis; T is temperature; and $a_{i,moist}$, $a_{i,FC}$, $a_{i,VM}$, and $a_{i,ash}$ are empirical Kirov correlation coefficients associated with moisture, fixed carbon, volatile matter, and ash, respectively.

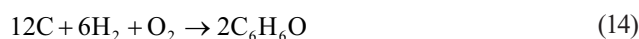
$$C_{p,i}^d = \sum_{j=1}^{ncn} w_j (a_{i,moist} + a_{i,FC}T + a_{i,VM}T^2 + a_{i,ash}T^3) \quad (3)$$

3.1.3 Heating value calculation

The composition and heating value were the most important parameters governing thermal processing [27]. It measures the chemical energy bound in a feedstock where this energy is released during combustion. Heating value is categorized into two, namely higher heating value (HHV) and lower heating value (LHV). The former involves condensation of the water in the combustion gases and thus the heat of condensation is also recovered, while the latter is when the water leaves as vapor. In some instances, the HHV and LHV are associated with the heat of vaporization of both HCl and water if the waste contains chlorine and produces HCl as one of the products. There are two methods for determining the heating values. First, experimentally using a full-scale boiler as a calorimeter and a laboratory bomb calorimeter and secondly, by calculation using empirical models. The most popular method for predicting heating value is linear regression due to its easier calculation and more cost-effective. The estimates were based on the general coal enthalpy model, including several correlations to compute the heat of combustion, heat of formation, and heat capacity.

3.1.4 Pyrolysis reaction

The pyrolysis reactor was modelled using a series of reactor blocks to capture the complex decomposition and secondary reaction behavior of plastic waste (PW). Initially, the dried solid PW feed was converted into a set of conventional components (i.e. C, H and O) using a FORTRAN subroutine embedded within a RYield block. This step represents the non-stoichiometric thermal decomposition of solid material providing a suitable input for the kinetic and thermodynamic reactor models. The output from the RYield block was then fed into an RPlug reactor followed by an RGibbs reactor, together representing the pyrolysis reaction system. Within the RPlug reactor, a total of 14 independent reactions, as defined in Eqs. (4)–(17), were assumed to occur simultaneously.



Plastic waste pyrolysis involves a complex network of random chain scission, β -scission, hydrogen transfer, isomerization, cyclisation, aromatization, and secondary cracking reactions. Therefore, the Eqs. (4)–(17) were not intended to represent elementary reaction pathways or to imply that only these reactions occur during pyrolysis. Instead, these reactions were introduced as lumped stoichiometric pathways in Aspen Plus to generate representative species required for process simulation, product separation, techno-economic assessment, and environmental analysis. The selection of hydrocarbons in Eqs. (4)–(17) was guided by experimental product distributions reported for polyolefin pyrolysis. Previous experimental studies have shown that LDPE and polyethylene pyrolysis produces light non-condensable gases such as hydrogen, methane, ethane, ethene, propane, propene, butane, and butene [9, 28]. In addition, gas chromatography – mass spectrometry (GC–MS) analysis of polyethylene and polypropylene thermal cracking products has reported broad distributions of condensable hydrocarbons, including alkanes, alkenes, dienes, and aromatic compounds [29, 30]. Based on these findings, methane, ethylene, ethane, and butane were used to represent the light

gas fraction, while heavier hydrocarbons were included as surrogate components for the condensable pyrolysis oil fraction. Aromatic compounds such as benzene, toluene, xylene, and naphthalene-type species were included to represent the aromatic fraction formed through secondary cracking and aromatization reactions.

Each reaction was modelled using first-order power law kinetics, operating in parallel to represent the formation of PPO and intermediate products. Hydrogen was selected as the base component for the kinetic expressions, with a reaction order of one, and only carbon and hydrogen were considered to participate in these reactions. Of the 14 reactions specified in the RPlug block, 11 reactions were defined in the vapor phase, with reaction rates expressed as functions of the partial pressure of hydrogen. This approach represents the dominant gas-phase cracking and reforming reactions occurring under pyrolysis conditions. The remaining reactions were modelled in the liquid phase, with constrained reaction extents to limit excessive product formation and thereby improve downstream separation efficiency and product purity. Following the kinetic reactor, the RGibbs block was employed to account for secondary equilibrium-driven reactions not explicitly captured by the kinetic model. By minimizing the Gibbs free energy of the system, the RGibbs reactor enabled the formation of additional species commonly observed in pyrolysis processes, including CO, CO₂, O₂ and oxygenated compounds such as phenol. These components were commonly present in pyrolysis gas but were not explicitly captured by the kinetic model. In total, 25 chemical components were defined in the Aspen Plus model, encompassing solid residues, gaseous products, condensable hydrocarbons, and minor oxygenated species. The model does not assume that only the reactions in Eqs. (4)–(17) occurred. Rather, these equations provide

a simplified representation of the dominant product families suitable for process simulation and techno-economic evaluation. Validation against detailed experimental product distributions, such as GC–MS data, is recommended for future improvement of the reaction network.

3.1.5 Process flowsheet

Fig. 2 illustrates the base case process flowsheet of the plastic waste pyrolysis system. The flowsheet was divided into upstream and downstream processes. The former involves two main sections, namely drying and reaction while the latter involve separation and distillation. The stream class for the upstream processes are set for MIXCINC and downstream processes were set for MCINCPSD. The latter includes particle size distribution (PSD) for char and ash. The drying section involves two blocks, RStoic (D-101) and Dryer (D101). RStoic block was used to convert part of the plastic into water. The wet feed then enters the Dryer block which simulate the removal of water from the plastic utilizing the hot flue gas from the heat exchanger (HEX).

The dry plastic was then introduced into a series of reactors that represent the pyrolysis reaction namely RYield (R-101A), followed by an RPlug (R-101AB) and RGibbs (R-101C). These reactors have specific functions to handle solid and nonconventional components suitable for pyrolysis reactions. The RYield block models the decomposition of dry plastic into its conventional components (C, H₂, N₂, O₂, H₂O, and ash). A FORTRAN subroutine was used to calculate the mass balance for the decomposition. The RPlug block then modeled the reaction kinetics of the pyrolysis reactions according to Eqs. (4)–(17). The reactor products then enter the RGibbs reactor, which accounts for secondary gas-phase reactions by minimizing the total Gibbs free energy of the system to form additional gaseous species namely CO, CO₂, O₂ and phenol.

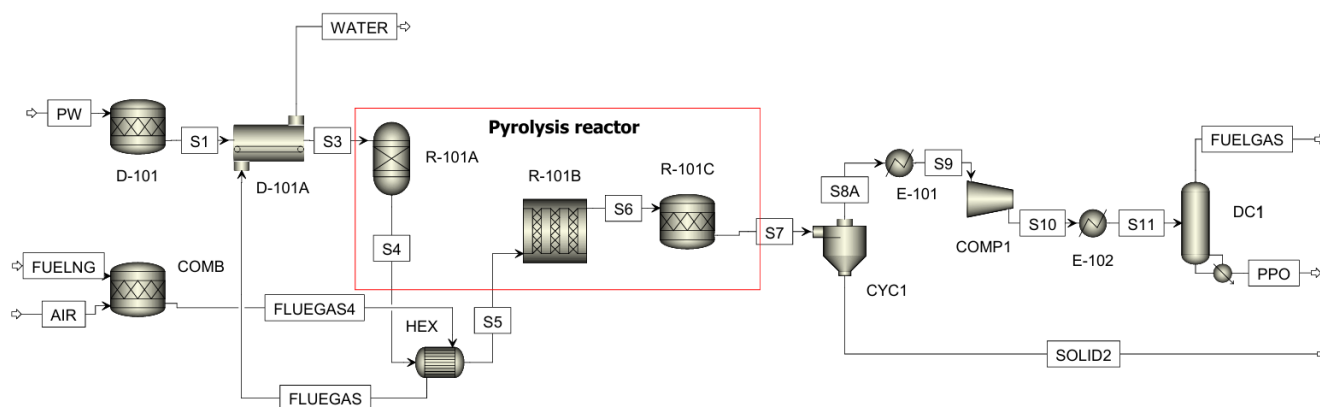


Fig. 2 Base case process flowsheet in Aspen Plus

To achieve the desired reaction temperature, a fired heater was used. To simulate this configuration, natural gas was combusted in an RStoic (COMB) block. The heat flue gas then went through a HeatX (HEX) block and exchanged heat with the cold dry plastic feed. This provides the required thermal duty and cost for heating the dry plastic feed to the pyrolysis temperature. Within the downstream processing, a Cyclone (CYC1) block was employed to separate char and ash based on its average PSD from the volatile gas stream. The pressure drop was set to 0.4 bar ensuring high separation efficiency. The gas stream was cooled by a cooler (E-101) before fed to a blower (COMPI) to increase the stream pressure for subsequent downstream processes. The subsequent treatment of the gas stream involves fractionating the non-condensable gases and liquid PPO. According to Krzywda and Wrzesińska [27], the design and methodology of the condensation system significantly impact the product quality. In a previous study by Zakaria et al. [31], presented at the International Conference on Chemical and Energy Engineering (ICChEE 2025), conventional coolers and flash drums were used to condense the pyrolysis gases and separate them from the non-condensable gaseous components. Alternatively, a distillation column using RADFRAC can be used with a partial condenser with vapor and liquid product stream [12].

In this work, the distillation column was configured without an overhead condenser. This configuration is commonly applied for non-condensable or light gas stream overhead products [32] where instead of using reflux loop, the feed stream was introduced at the top stage of the column that act as reflux by providing liquid holdup and thermal conditioning at the column inlet. Under this operating strategy, the heavier PPO components (C7-C20) condensed and flowed downward, accumulating in the bottom product stream. Conversely, the overhead vapor stream contains mostly hydrogen, methane, and ethene exited the column as the distillate. In industrial practice, such light-end off-gas streams are frequently utilized as supplementary fuel or heat sources for fired heaters, boilers, or cogeneration units [33]. The column was modelled using equilibrium-stage approach in RADFRAC block with 18 theoretical stages. The detailed operating specifications, design parameters, and functional roles of the main unit operations are summarized in Table 6.

3.2 Validation and statistical analysis

The higher heating value of the simulated pyrolysis products was used as a key validation parameter. As HHV provides a measurement of the energy content of the product

streams and indicates the combined effects of reaction kinetics, product distribution, and elemental composition, a good agreement between simulated and reported HHV values shows that the model adequately captures the energy balance and dominant reaction pathways of the pyrolysis process. To validate the model, the calculated HHV of PPO were compared with experimental value reported by Faisal et al. [17]. To calculate the statistical percentage error, Eq. (18) was used:

$$\text{Error}(\%) = \left[\frac{(y_i - \hat{y}_i)}{y_i} \right] \times 100\%, \quad (18)$$

where Error (%) is the percentage error, y_i is the experimental value for observation i , and $\hat{y}_i$ is the corresponding predicted value. The subscript i denotes the observation or data-point index, while the factor 100% converts the relative error into percentage form. In general, errors of less than 10% give excellent prediction whereas 10–20% gives good prediction.

3.3 Economic analysis

In this work the estimation and analysis of plastic waste pyrolysis economic feasibility were based on the capital expenditure (CAPEX) and operating expenditure (OPEX) cost metrics. The methodology was based on a framework established by Peters et al. [20] and Turton et al. [34] and has been widely adopted by researchers for various techno-economic assessments (TEA) of chemical processes including plastic waste pyrolysis [35]. CAPEX was estimated based on the total capital investment, C_{TCI} as defined in Eq. (1):

$$C_{\text{TCI}} = C_{\text{TFCI}} + C_{\text{C}} + C_{\text{WC}}, \quad (19)$$

where C_{TPCI} is the total fixed capital investment combining direct costs for equipment, installation factors, including piping, instrumentation, electrical, civil, insulation and indirect costs, such as engineering and project management. C_{C} are the contingency costs (10–15% of C_{TPCI}) and C_{WC} is the working capital costs (5% of C_{TPCI}). OPEX on the other hand was calculated based on the annual operating costs of raw material and fuel consumption, utility usage, maintenance and labor costs and consumables and waste disposal. These costs were derived directly from process simulation outputs.

In this work, Aspen Process Economic Analyzer (APEA) tool was used to perform cost estimation and economic evaluation. APEA utilizes equipment specifications, operating conditions, equipment sizing data, and material and energy balance information generated from

Table 6 Summary of main unit operations specifications and functions

Model ID	Block ID	Specification	Function
RStoic	D-101	120 °C, 101.325 kPa Conversion of plastic to water (0.1275%)	To model the fractional conversion of solid plastic waste into water.
Dryer	D-101A	>100 °C, No pressure drop Utility: Flue gas	To model the separation of water from plastic waste using hot flue gas
RYield	R-101A	>100 °C, No pressure drop	To convert the NC solid plastic into conventional components with FORTRAN subroutine.
RPlug	R-101B	Kinetic based model 500 °C, No pressure drop Length: 16 m, Diameter: 0.75 m	A rate-based reactor to model the pyrolysis reactions to produce liquid and vapor product.
RGibbs	R-101C	500 °C, No pressure drop	To model the secondary gas-phase reactions for formation of CO, CO ₂ , O ₂ , and phenol based on free Gibbs energy.
RStoic	COMB	101.325 kPa, 0 heat duty*, Combustion reaction	To model the generation of hot flue gas by combustion of natural gas.
HeatX	HEX	Cold out <i>T</i> 500 °C, No pressure drop	To increase the dry feed temperature to pyrolysis temperature by exchanging heat with hot flue gas.
Cyclone	CYC1	<i>T</i> 500 °C, Pressure drop of 0.4 bar >99.9% removal of ash and carbon.	To remove solid component i.e. char and ash according to its particle size distribution.
Cooler	E-101	Output <i>T</i> 169 °C, No pressure drop Utility: Air	To cool down the hot vapor temperature suitable for blower operation.
Compr	COMP1	Type: Fan blower Discharge pressure at 1.5 bar. Utility: Electricity	To compress input stream to 1.5 bar while maintaining gas phase.
Heater	E-102	Type: Cooler 41 °C, No pressure drop Utility: Air	To cool down the compressed gas suitable for fractionation operation.
Radfrac	DC	No of stages: 18 Bottom <i>T</i> 140 °C, Column pressure 101.325 kPa No condenser, Kettle reboiler Utility: Medium pressure steam	To separate vapor (<C6) and liquid (≥C6)

* A heat duty of 0 kW indicates that the COMB reactor is operated adiabatically, with no external heat added or removed.

Aspen Plus simulations to estimate CAPEX and OPEX. This integration ensures consistency between process performance and economic assessments while minimizing manual data transfer errors. Equipment costs were estimated using the built-in APEA cost correlations, which are based on industry-standard methodologies and adjusted for equipment size, material of construction, operating pressure and temperature, and plant capacity. Cost estimates were further updated using the Chemical Engineering Plant Cost Index (CEPCI) to account for inflation and current market conditions.

Based on the estimated CAPEX and OPEX values, key economic performance indicators, including net present value (NPV) and payback period, were calculated over a project lifetime of 20 years. These indicators enabled a direct comparison between alternative process configurations and base case flowsheet. A plant availability of 52 weeks/y, and straight-line depreciation method were

assumed throughout the analysis. Table 7 [36–38] shows the main plant specifications and selected input parameters adopted in APEA to establish the cost estimation framework. Note that for the base case scenario a fully subsidized raw material was adopted. A sensitivity analysis was performed to analyze the effect of raw material subsidy on economic performance.

3.4 Environmental analysis

Environmental performance was assessed through Scope 1 and Scope 2 greenhouse gas (GHG) accounting framework. Scope 1 includes direct GHG emissions arising from on-site fuel combustion and process-related reactions, while Scope 2 accounts for indirect emissions associated with purchased electricity and imported utilities. The key performance indicator is CO₂-equivalent (CO₂e). CO₂e represent the combined climate impact of greenhouse gases expressed as an equivalent amount of CO₂ using Global

Table 7 Plant specification and selected parameters for economic analysis in APEA

Parameters	Value
Plant operation	52 week/y
Total feed flowrate of mixed PW	6,850 kg/h
- PP	3,425 kg/h
- HDPE	1,712.5 kg/h
- LDPE	1,712.5 kg/h
Raw material cost	
- Mixed plastic waste	RM 1.5/kg
- Waste subsidy (full)	(RM 0.42/kg)
- Natural gas	RM 35/MMBtu* [34]
Product price	
- PPO	RM 2.33/kg
- Char	RM 0.8/kg
Utility cost	
- Electricity	RM 0.2983/kWh [35]
- Middle steam pressure	RM 0.063/kg [36]
Working capital	5%
Plant overhead	50%
Operating charger	25%
Cost/operator · h**	RM 84 (USD 20)
Cost/supervisors · h**	RM 147 (USD 35)
Maintenance cost/8000 h	RM 211,250 (USD 50300)

* MMBtu refers to one million British thermal units. The natural gas price of RM 35/MMBtu represents a cost of RM 35 per 1 MMBtu of natural gas.

** 'Cost/operator · h' and 'Cost/supervisor · h' refer to the hourly labor cost per operator and per supervisor, respectively.

Warming Potential (GWP) factors, typically over a 100-year time horizon (GWP_{100}), as defined by the IPCC. CO_2e is calculated by Eq. (20):

$$CO_2e = \sum_i (E_i \times GWP_i), \quad (20)$$

where E_i is the mass of greenhouse gas i emitted and GWP_i is the global warming potential of gas i relative to CO_2 . Using a single indicator provides direct comparison across alternative process designs, operating conditions, and baseline technologies. When employed with Aspen Plus it provides detailed mass and energy balances along with the fuel consumption rates, process vent and exhaust compositions, utility demands and heat recovery and recycling opportunities which serve as the primary input for emission calculations. This ensures consistency between technical performance and environmental assessment.

4 Results and discussion

4.1 Simulation

Table 8 shows the summary of the simulation mass balance results. The simulation results correspond to approximate mass yields of 68.5% PPO, 3.6% char, and 27.8%

Table 8 Simulation results summary

Component	Flowrate, kg/h
Product	
- Pyrolysis product oil	4692
- Char	248
- Fuel gas	1902

fuel gas from a feed rate of 6,850 kg/h of mixed plastic waste. The simulated mass balance demonstrates good agreement with reported ranges for plastic waste pyrolysis [12, 27], with liquid oil as the dominant product, followed by fuel gas and a minor fraction of char. Fig. 3 shows the liquid oil composition which is predominantly composed of middle-distillate and aromatic hydrocarbon fractions. The former shows high presence of $C_{14}H_{30}$ (25.8%), $C_{16}H_{34}$ (10.2%) while the latter mainly consists of C_7H_8 (23.5%), and C_8H_{10} (17.9%). The high proportion of high aromatic compound can enhance the overall calorific value of the liquid PPO and potential use as fuel blending components or chemical feedstocks. From the energy calculations, the simulation yielded some important results. By describing the targeted PPO property, HHV, the result shows the simulation met the PPO specification. The simulated value was 36.36 MJ/kg compared to the experimental value of 39.47 MJ/kg [17] with error of 7% indicating the model gives very good predictions. Apart from that, a significant amount of fuel gas generated provides an opportunity for heat utilization to offset external energy demand which will be discussed further.

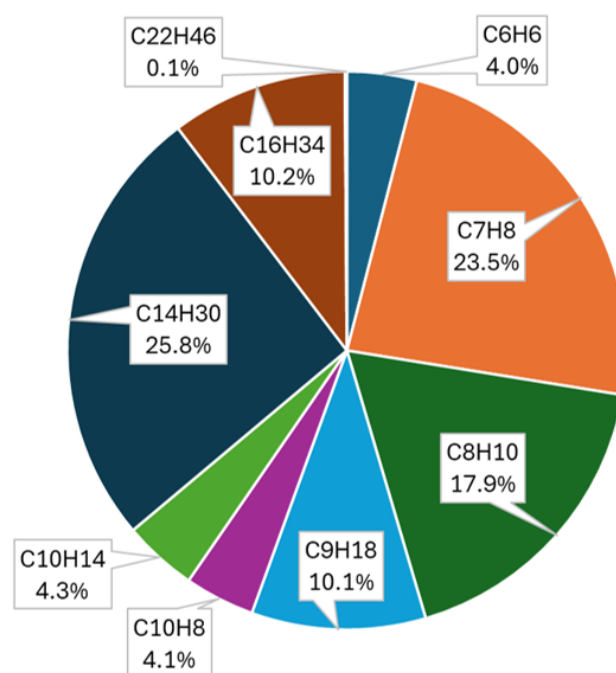


Fig. 3 Component mol % of liquid PPO

4.2 Economic evaluation

Table 9 shows the breakdown of capital and utility cost by major unit operations. The distillation column accounts for the largest investment with 27.7% of total capital expenditure followed by the pyrolysis reactor with 17.3%. The high cost is due to its size and complex equipment requirements for separation and high temperature system. Gas handling and heat transfer units, including the fan blower, E-101, and E-102, each contribute approximately 13% of the total capital cost. Auxiliary units, i.e. dryer and cyclone account for relatively small capital costs of 5.5% and 1.3%, respectively. The results indicate that major capital investment concentrated in reaction and separation units. For utility cost, the result shows that the fan blower and distillation column dominate the operating energy demand of the process.

Electrical utility is associated with the fan blower whereas distillation column is associated with the use of medium-pressure steam. Heat exchange duties in E-101 and E-102 rely on ambient air that results in negligible utility costs. Dryer and HEX utilize hot flue gas from the combustion of natural gas. Note that consumption of natural gas was counted as raw material in economic analysis. Operation costs for cyclone operation were assumed negligible. Table 10 summarizes the overall economic performance.

Table 9 Main unit operation capital cost and utility cost

Equipment	Capital cost, RM	Utility cost, RM/y	Capital cost, %
Dryer (D-101A)	720,417	–	5.5%
Pyrolysis reactor (R-101B)	2,263,750	–	17.3%
Cyclone (CYC1)	165,000	–	1.3%
Fan blower (COMP1)	1,715,000	295,594	13.1%
Distillation column (DC1)	3,620,417	485,881	27.7%
E-101	1,721,250	–	13.2%
E-102	1,693,750	–	13.0%
HEX	1,162,917	–	8.9%

Table 10 Summary of economic analysis

Indicator	Value
Total CAPEX, MYR*	17,013,708
Total OPEX, MYR/y	80,753,333
Total raw materials cost, MYR/y	68,712,083
Total product sales, MYR/y	97,548,333
Total utilities cost, MYR/y	921,171
Payout period, y	5.85
Net present value, MYR	5,410,000

* MYR refers to Malaysian Ringgit, the currency of Malaysia.

The total capital investment is estimated at RM 17.01 million, while the annual operating expenditure amounts to RM 80.73 million. OPEX is strongly dominated by raw material costs, namely plastic waste (95%) and natural gas (5%), which account for RM 68.71 million/year, representing 85% of total operating costs. Utility costs are comparatively low, less than 1 million/year. Annual product sales revenue is estimated at RM 97.55 million. Overall, the economic indicators demonstrate favorable project viability, with a payout period of approximately 5.85 years and a positive net present value of RM 5.41 million after 10 years. These results suggest that the process is economically feasible under the assumed market and operating conditions, while also revealing that the cost of plastic waste feedstock is a critical determinant of overall project performance. To elucidate this dependency, a sensitivity analysis was performed to analyze the influence of varying plastic waste feedstock prices, expressed in terms of subsidy levels, on the corresponding payout period. The results of this analysis are presented in Fig. 4. It is evident from the results, as the PW price increases from RM 1.08/kg (base case) to RM 1.19/kg or subsidy reduction from 28% to 21% the payout period increases significantly from approximately 5.85 years to 9.47 years. This represents an increase of 62% in payout period for a relatively small increase in feedstock price. The results show a strong dependence of project profitability on PW price thus highlighting feedstock cost as a critical economic driver for the pyrolysis process.

4.3 Environmental analysis

The breakdown of Scope 1 and Scope 2 CO₂e emissions results for the output streams and utilities is presented in Table 11. The total greenhouse gas emitted is 16,864.9 CO₂e kg/h, of which Scope 1 emissions

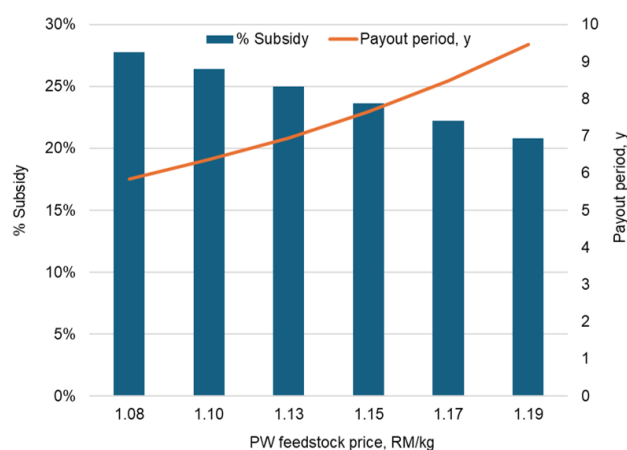


Fig. 4 Sensitivity analysis of varying plastic waste feedstock prices to subsidy levels and payout period

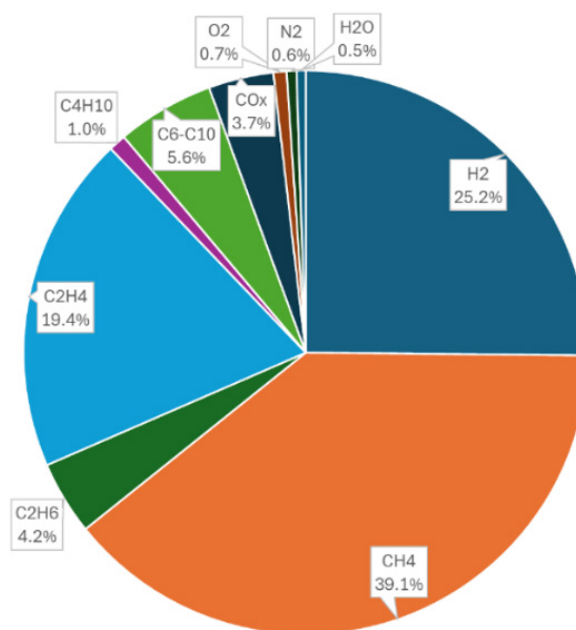
Table 11 Summary of environmental analysis for the output streams and utilities

Item	Scope 1, CO ₂ e kg/h	Scope 2, CO ₂ e kg/h	Overall contribution (%)
Output stream			
- Fuel gas	16,176.1	-	95.9%
- PPO	0	-	0%
- Water	572.1	-	3.4%
Utilities			
- Fan blower (COMP1)	-	52.1	0.3%
- Distillation column (DC1)	-	64.6	0.4%
Total	16,748.20	116.7	
Total overall	16,864.90		

dominate, contributing more than 99%, while Scope 2 emissions account for only less than 1%. Scope 1 emissions are almost entirely attributed to the flue gas stream from on-site combustion of fuel gas for process heating. Scope 2 emissions on the other hand are associated with purchased electricity and utilities, contributing only 116.7 CO₂e kg/h. The results show that carbon intensity is strongly driven by on-site fuel combustion rather than grid electricity usage. Consequently, heat utilization measures could offer potential for reducing the overall CO₂e footprint of the pyrolysis system. The analysis of heat utilization will be presented next. The total greenhouse gas emitted is 16,864.9 CO₂e kg/h, of which Scope 1 emissions dominate, contributing more than 99%, while Scope 2 emissions account for only less than 1%. Scope 1 emissions are almost entirely attributed to the flue gas stream from on-site combustion of fuel gas for process heating. Scope 2 emissions on the other hand are associated with purchased electricity and utilities, contributing only 116.7 CO₂e kg/h. The results show that carbon intensity is strongly driven by on-site fuel combustion rather than grid electricity usage. Consequently, heat utilization measures could offer potential for reducing the overall CO₂e footprint of the pyrolysis system. The analysis of heat utilization will be presented next.

4.4 Analysis of heat utilization

Referring to the base case scenario, the amount of fuel gas released was 1,904 kg/h. The gas component and its molar percentage is shown in Fig. 5. The gas is largely composed of methane (39.1%), hydrogen (25.2%), and ethene (19.4%) with HHV of 48.94 MJ/kg which is comparable to refinery fuel gas. Utilizing the gas as fuel enables effective internal

**Fig. 5** Component mole % of the fuel gas stream

heat integration, reducing external fuel consumption. To incorporate the pyrolysis gas as an internal fuel source for process heat integration, the pyrolysis flue gas natural gas was split into two streams. One stream was mixed with the natural gas and the other was vented. This configuration allows the flue gas to be integrated as internal heat source for the pyrolysis reactor and dryer. The modified process flowsheet utilizing the flue gas and integrating with the heat exchanger is shown in Fig. 6. The modified flowsheet successfully converged and the results comparing techno-economic and environmental analysis with the base case are shown in Table 12. The comparative assessment shows that the total CAPEX has reduced slightly by 1.0%, however, the total OPEX decreases by 4.6% and raw material costs reduced by 5.0%. This significant reduction is due to lower external fuel and utility requirements after the heat-integrated configuration.

These cost savings translate into a significant improvement in project profitability, as the payout period reduced from 5.85 to 4.76 years, corresponding to 18.7%. The implementation of heat utilization also leads to a substantial reduction in greenhouse gas emissions across both direct and indirect sources with total improvement of 10.7%. The improvement is primarily due to some portion of the pyrolysis fuel gas being recycled internally to the fired heater thus reducing the amount of fuel gas emitted to the environment. The heat utilization delivers meaningful economic and environmental performance but marginal impact on capital investment.

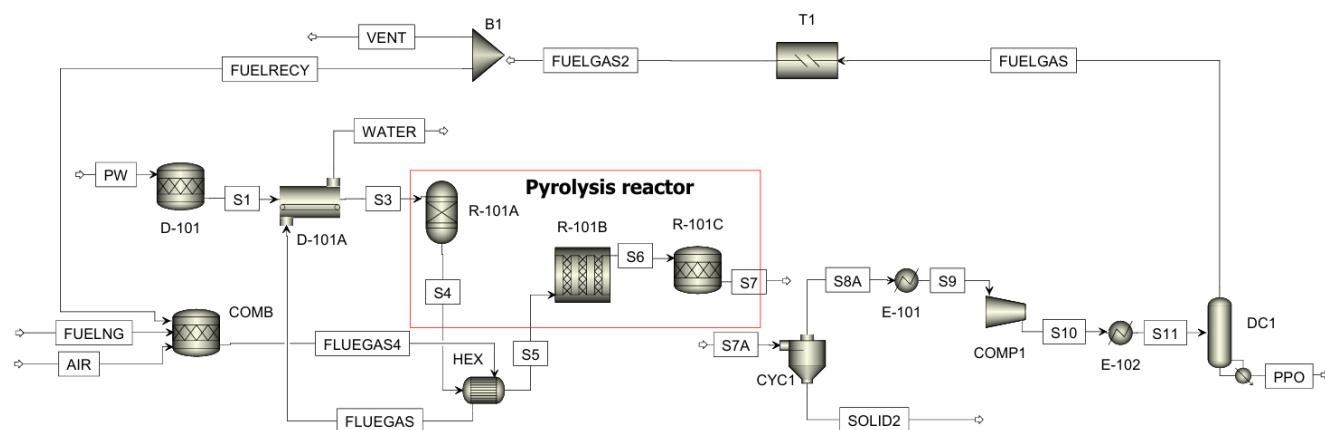


Fig. 6 Modified process flowsheet utilizing fuel gas stream as heat source

Table 12 Economic and environmental comparison between base case and case with heat utilization

	Base case	With heat utilization	% diff
Total CAPEX, MYR	17,013,708	16,842,083	1.0%
Total OPEX, MYR/y	80,753,333	77,074,167	4.6%
Total raw materials cost, MYR/y	68,712,083	65,305,833	5.0%
Payout period, y	5.85	4.76	18.7%
Total CO ₂ e kg/h	16,864.9	15,067.7	10.7%

5 Conclusion

This study presents an integrated simulation-based techno-economic evaluation, and environmental analysis of mixed plastic waste pyrolysis under Malaysian operating and market conditions. A rigorous Aspen Plus model was successfully developed and provided good predictive capability. Results indicate that PPO is the dominant product with substantial production of fuel gas and could offer potential internal heat recovery. The techno-economic analysis shows that the proposed plant configuration is financially viable with a positive net present value and reasonable payout period. However, it is highly sensitive to plastic waste price and subsidy level, where a 7% reduction in subsidy could increase the payout period by approximately 60%. It is important to note that a well-developed plastic waste supply network, supported by strong

markets, labor availability, and infrastructure, significantly enhances the viability of plastic waste pyrolysis. Environmental analysis identifies direct emissions from on-site fuel combustion as the primary contributor of CO₂ emissions. In contrast, emissions associated with electricity consumption are relatively minor. The utilization of internally generated fuel gas has shown reduction in total operating expenditure by 4.6% and shortens the payout period by 18.7%, while decreasing the overall CO₂e emissions by 10.7%, with minimal impact on capital cost. These demonstrate that internal heat utilization improves both the economic viability and decarbonization performance of the process. The findings provide quantitative evidence that plastic waste pyrolysis can play a meaningful role in Malaysia's waste management and circular economy strategies. The outcome of this study could serve as a basis for developing and expanding pyrolysis plants in Malaysia and encourage investment into alternative methods of plastic waste management.

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