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Sustainable Syngas Production: Economic and Circular Economy Benefits of PET Waste Gasification

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Abstract

This paper promotes awareness of the circular economy as a superior waste disposal system alternative. The novelty of this study is to model cleaner energy generation from the gasification of polyethene terephthalate (PET) waste accompanied by a detailed analysis on the economic feasibility. In the approximate analysis of PET, the percentage values for Ash and hydrogen were low (0 and 4.21, respectively). This parameter significantly impacted the Ash and hydrogen contents of the output gas, as it directly influenced the PET feedstock to a more excellent heating value (23.34MJ/kg) and lower heating value (10.63MJ/kg). Temperature and pressure are treated as free variables throughout each block during the gasification procedures. A sensitivity study revealed that the PET moisture content has no significant effect on the product composition. The economic analysis indicated that the gasification process could be economically viable. The economic analysis of the process considered the comprehensive evaluation of the plant's financial aspects. The economic evaluation indicated that the facility would reach the break-even point by the end of its third year of operation, demonstrating its economic viability, with an NPV of £77,574,506.37 and an ROI of 40.1% for the suggested 25-year operational period of the facility.

Keywords: Gasification; Polyethylene Terephthalate; Economic Viability; Circular Economy; Sustainable Energy Generation; Waste Management.

1. Introduction

Plastics are light, stable, and adaptable, allowing them to be utilised in various applications. As a result, production has grown at a rate that has never been witnessed since 1950 [16]. In 1950, only 1.5 million tonnes of plastics were manufactured annually [37]. However, recent changes in the business world have made it more essential to make plastic. In 2020, statistics showed 367 million tonnes of plastic were produced and that the global production of thermoplastics will reach 445 million tonnes in 2025 and 589 million tonnes in 2050 [37].

A massive percentage of Municipal solid waste (MSW) is plastic, with Polyethene terephthalate (PET), high-density polyethene (HDPE), polyvinyl chloride (PVC), low-density polyethene (LDPE), polypropylene (PP), and polystyrene (PS) being the most prevalent types [31]. PET, constituting approximately 7% of global plastic consumption, is extensively utilized in packaging and various food products due to its lightweight and high-pressure resistant properties [22]. However, the escalating use of PET has led to a surge in its waste, exacerbating the global environmental challenge of plastic disposal [14]. Formerly, all plastic waste was landfilled or incinerated, but dwindling landfill capacity, and increasing environmental concerns necessitate alternative waste management strategies [9]. PET polymer's minimal degradability at room temperature and slow reaction rates renders this pathway unfavorable. Nonetheless, incineration yields hazardous compounds, including polychlorinated biphenyls, aromatic hydrocarbons, and toxic free radicals rich in carbon and oxygen [43]. The considerable issue associated with PET waste resides in its intrinsic non-degradable nature, posing an environmental detriment.

Effective waste management techniques have redefined plastic waste as a sustainable energy resource through thermochemical processing systems such as pyrolysis, co-pyrolysis, and co-gasification [32, 40, 44, 45]. Co-gasification of plastics with biomass yields high-calorific producer gas, while pyrolysis produces valuable hydrocarbons for energy or chemical feedstock use [46, 48]. Lee et al. (2022) found that these methods effectively convert waste into valuable combustible gases, offering benefits such as reduced toxin emissions and volume reduction [21]. Additionally, co-gasification or co-pyrolysis can optimize gaseous product formation, as seen in the transformation of PET waste into syngas, with potential fuel yield enhancement [20].

Honus et al. (2018) compare the fuel properties derived from the pyrolysis of PE, PP, PS, PVC, and PET to those of natural gas (NG) and propane. Honus et al. (2018) discovered that PET had higher laminar burning velocities and heating values than NG (36.1 CmS^{-1}), while PVC's (178.62 CmS^{-1}) is almost five times higher than NG [17].PET demonstrates significant combustion value as an energy source, dependent on temperature changes, reacting upon heating, releasing hydrocarbons at high temperatures, and transitioning into a liquid phase, with gas and liquid product compositions influenced by fuel content. Net and gross calorific values are critical factors determining energy quality, representing the chemical energy stored per unit of matter or volume of specific fuel [3].

This study aims to assess the feasibility and conduct a techno-economic analysis of co-gasifying PET plastic bottles using basic equipment to address plastic waste management. Additionally, it will explore gasification parameters to generate syngas for energy production in a gas engine, with the overarching goal of promoting a cost-effective approach for the circular economy as a more effective solution for PET waste disposal. model for producing cleaner energy from waste. Through the transition to a circular economy, this design will strive to reduce global waste by a net amount.

2. Model development and process simulation

2.1. Modelling

The Aspen Plus simulation is utilised to construct and assess a digital prototype of a physical model to anticipate the performance of a gasification process and examine the practicality of the system [30, 35, 39, 47]. Figure 1 shows the block flow diagram of a gasification process. The drying process was based on data from proximate analysis of the feedstock. The water content of the fuel was separated from the stream at this step. The moisture is vapourised as the PET fuel is dehydrated. The details of the process are given in Appendix A.

The Aspen integrated unit operation library modelled the complete gasification process in two stages. Appendix A1.6 covers the two phases, pre-processing and gasification, separately. The performance of the gasification process was investigated using hydrogen production calorific value as operating parameters. The decomposition step takes place in the pyrolyser, and the yield of products was calculated using an integrated calculator block in Aspen Plus. The conventional components used were hydrogen, methane, carbon monoxide, carbon dioxide, oxygen, nitrogen, carbon, sulphur, PET, and ASH. The PET is defined by its final and proximate analyses. Therefore, PET and ASH were defined as nonconventional

components. The HCOALGEN and DCOALIG computed the PET formation enthalpy and density [33]. In a standard gasification procedure, the fuel is initially pyrolysed by adding external heat, breaking it into smaller constituent components. No unique block in this design can represent the gasification reactor. Therefore, a combination of two or more blocks is required for gasifier modelling [13]. Two reactors, the R-Yield and the R-Gibbs block [42], were used to represent the gasification process. Figure 2 depicts a block flow diagram for the Gasification processes of PET. The following sections cover each of the two phases separately.

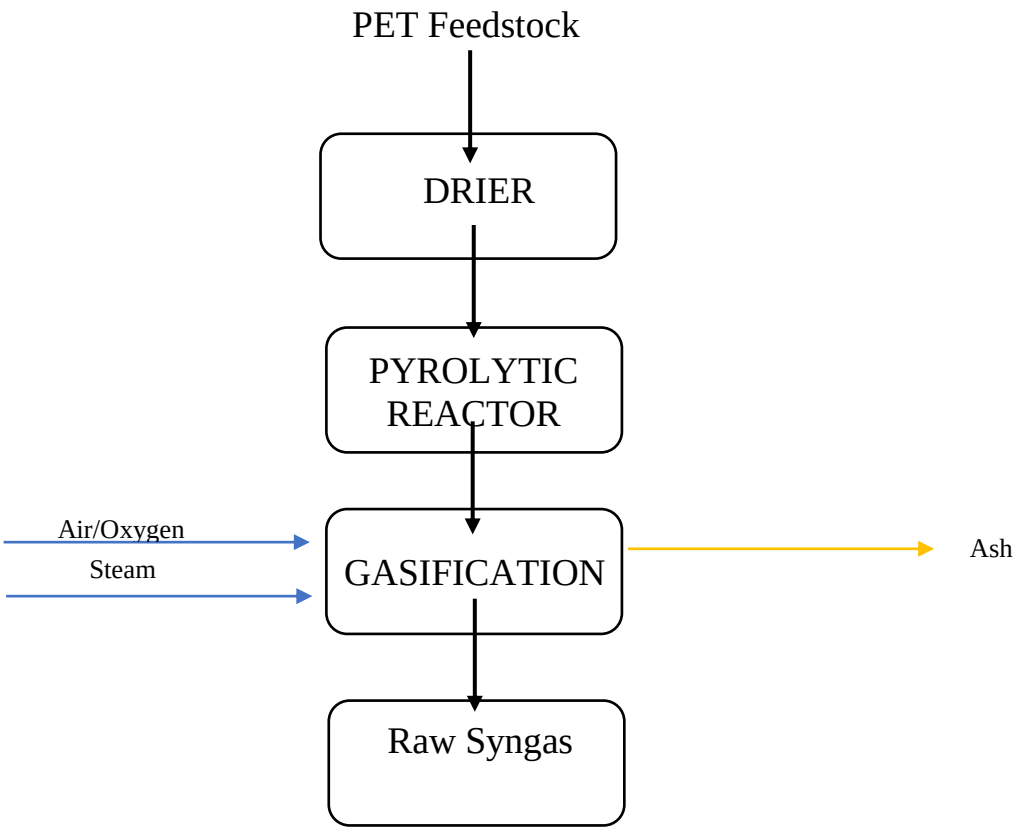

Figure 1: Block flow diagram for the Gasification processes of PET.

2.2. The higher heating value (HHV) of PET

The PET waste feedstock was modelled by considering the proximate and ultimate analysis of the fuel. The elemental composition includes 62.5 wt.% carbon, 33.29 wt.% oxygen, and 4.21 wt.% H_2 on a dry ash-free basis. In general, no ash content was found for PET on a dry basis. However, Fivga and Dimitriou (2018) studies showed that the ash

content is too low to significantly affect the overall mass balance of the process and should be set to zero [10]. The higher heating value (HHV) of the PET feedstock is calculated using the following formula [6]:

$$HHVdry(MJ/kg) = 0.3491^{*}C + 1.1783^{*}H + 0.1005^{*}S - 0.1034^{*}O - 0.015^{*}N - 0.0211^{*}A$$

Eqn. (1)

Where and represent mass percentages on a dry basis of oxygen, carbon, nitrogen, sulphur, and ash contents of feedstock, respectively.

The lower heating value (LHV) of the PET feedstock is computed using the formula below [6]:

$$LHV\ dry\ (Mj/kg) = HHV\ dry - 2.442^{*}8.396^{*}(H/100) \qquad Eqn.(2)$$

The HHV of dry plastic waste used in this study is calculated using Eq. 1 and amounts to 23.34MJ/kg, while the LHV is calculated using Eq. 2 and amounts to 10.63MJ/kg. This agrees with the literature values [7]:

2.3. Model validation

The critical model for the gasification process was created using Aspen plus embedded modules centred on simulations extensively deployed in the research journals. To test the applicability of the present model, simulations of waste PE gasification in a fluidised bed reactor were conducted, and the results were compared with those of Kannan et al. (2013) [18]. It was found that their equilibrium model allows one to control the effect of the PE gasification process under different operating conditions. This model was selected due to its similarity to the present study. In addition, to evaluate the dynamic performance of the PET gasification process, an analysis of a similar nature was conducted in this work. This research will simulate the laboratory results obtained from Pohořelý et al. (2006) [34].

2.4. Assumption

In the current study, the following assumptions are assumed for the development of the process model:

1. The process is in a steady state.
2. It was considered that all chemical reactions within the gasifier had reached equilibrium.
3. The system considered was assumed to be an isolated system, so there is no consideration of pressure drop or heat loss as they are all constant.

4. Only methane, hydrogen, carbon monoxide, carbon dioxide, oxygen, and water were present in the product stream.
5. The char component was assumed to be pure carbon as neither the ultimate nor the proximate examination revealed the presence of Ca, K, Na, P, Si, and Mg.

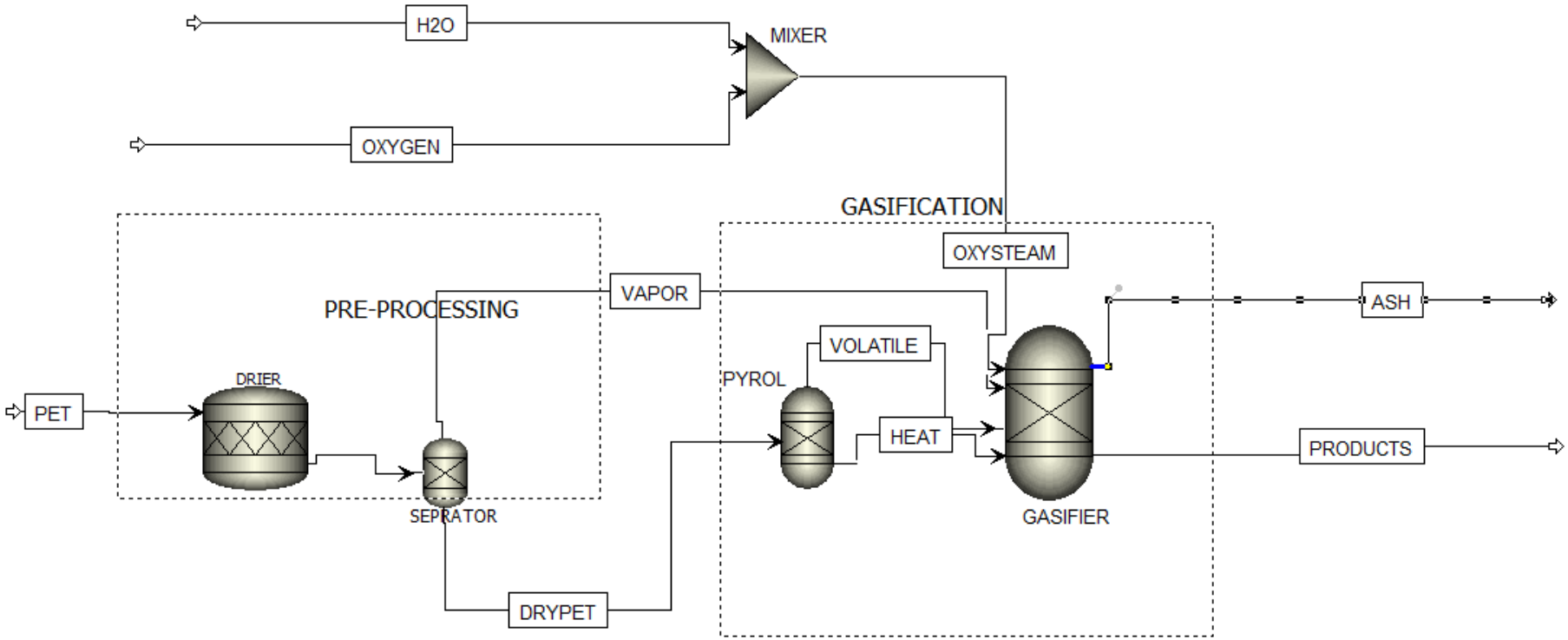

Figure 2: Process flowsheet of a PET gasification process in Aspen Plus.

3. Result and Discussion.

3.1. Validation of the model

Similar to the present work, Kannan et al. (2013) used a reference study to validate the model. Using their model, Kannan et al. (2013) examine the simulation of PE gasification in a fluidised bed reactor. In their study, Kannan et al. (2013) developed an equilibrium model that predicts the behaviour of the PE gasification process under different operating conditions. This study will simulate the gasification of PET blends using an Aspen Plus equilibrium model.

This study and Kannan et al. (2013) work on the gasification agent are significant differences. According to the cited study, Steam gasification means that more heavy hydrocarbons, or tars, are made, making the model more complex to understand because of the reactions that create the tars. However, the formation of heavy hydrocarbons is excluded from the simulation because it is unlikely to occur under equilibrium conditions. Due to this assumption, the only modification made to the model of this work was the addition of oxygen as the gasification agent compared to the reference gasification process. Sundararajan et al. (2017) argue that gasification with oxygen/steam is an attractive alternative for avoiding the harmful effects of fly ash in combustion products [38].

Additionally, oxygen was added to the steam to maximise CO production. The Distinctive features of the proximate and ultimate PE and PET analysis values demonstrate why oxygen was added as a gasifying agent. The percentage values for Ash and H_2 were 0 and 4.21, respectively. With this input, the Ash and H_2 contents of the product gas were distinct compared to Kannan et al. (2013). Thus, the steam/oxygen flow was slightly reduced to compensate for the deficiency of CO and H_2. This conclusion was reached because the reference study did not emphasise whether they restrict the chemical equilibrium concerning the gasification reactions undergone in the gasification (Gibbs reactor) block.

3.2. Sensitivity analysis

3.2.1. PET moisture content

The PET moisture content was found to have no significant effect on the composition of syngas or other products. Therefore, throughout this sensitivity study, the mass fraction of the product was maintained at its respective base case value. Figure 3 illustrates the correlation between the mass fraction derived from each component of the products and the percentage composition of the moisture content as determined by the proximate analysis of

the PET. Figure 3 illustrates how altering the feed moisture content affects the final output. The product composition is unaffected by the moisture content, as would be expected. At 0.51 *Kg/hr*, $CH_4's$ composition remained at its peak level. This result validates Motta et al. (2018) review on biomass gasification in fluidised beds [38].

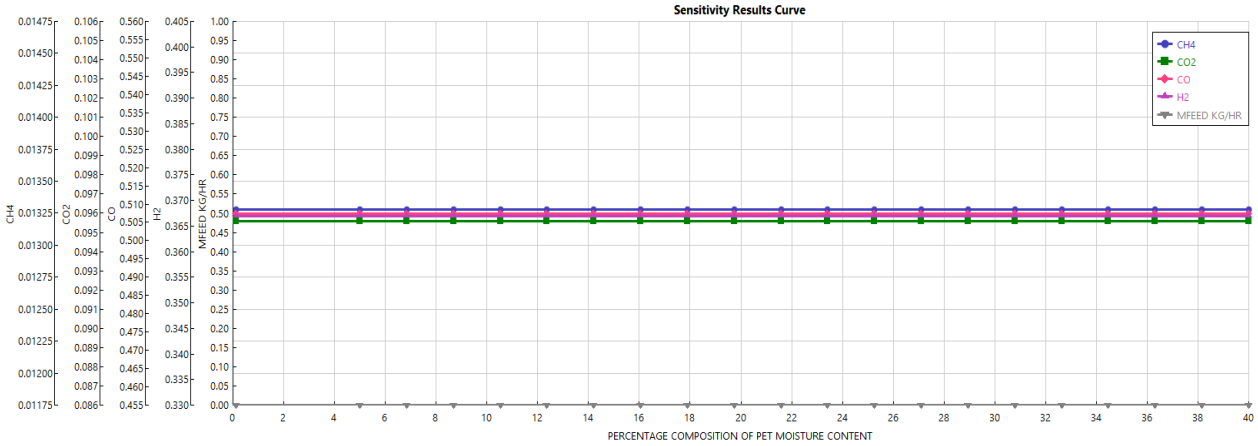

Figure 3: Effect of PET moisture content on syngas, CH_4, and CO_2 composition.

3.3.2. Effect of Gasification Agent on PET.

The effect of the oxygen/steam-to-PET mass ratio on PET gasification was studied using a steady PET feed rate of 6 *kg/h*. At low amounts of water, oxidation processes via Reactions (3-5) would likely predominate, resulting in a higher temperature.

The reactions given here should have been given under the model description.

Reactions with oxygen [23]:

$$C + \frac{1}{2}O_2 \leftrightarrow CO; \quad \Delta H°_r = -112\ kJ/mol \qquad Eqn.(3)$$

$$CO + \frac{1}{2}O_2 \leftrightarrow CO_2; \quad \Delta H°_r = -283\ kJ/mol \qquad Eqn.(4)$$

$$H_2 + \frac{1}{2}O_2 \leftrightarrow H_2O; \quad \Delta H°_r = -248\ kJ/mol \qquad Eqn.(5)$$

These temperature changes would accelerate the reactions of CO, H_2, CO_2, and CH_4 with H_20, which, according to the chemical equilibrium principle, would foster the generation of CO and H_2, as shown in Reactions (6-8).

Reaction with water [23]:

$$C + H_2O \leftrightarrow CO + H_2; \quad \Delta H°_r = 136\ kJ/mol \qquad Eqn.(6)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2; \quad \Delta H°_r = -35\ kJ/mol \qquad Eqn.(7)$$

$$CH_4 + H_2O \leftrightarrow CO + 3H_2; \quad \Delta H°_r = 206\ kJ/mol \qquad Eqn.(8)$$

In addition, the hydrogen allowed to react with carbon will promote methane synthesis according to Reactions (9–11).

Methanation reaction [23]:

$$C + 2H_2 \leftrightarrow CH_4; \quad \Delta H°_r = -74.8\ kJ/mol \qquad Eqn.(9)$$

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O; \quad \Delta H°_r = -225\ kJ/mol \qquad Eqn.(10)$$

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O; \quad \Delta H°_r = -190 kJ/mol \qquad Eqn.(11)$$

The resulting methane would combine with the extra steam, as indicated in reaction (8), to produce CO and H_2 [18]. Generally, at any oxygen/steam-to-PE ratio, the equilibrium system temperature and product composition would result from concurrent endothermic and exothermic reactions. Figure 4 depicts the relationship between the oxygen/steam-to-PET ratio, product mass fraction, and equilibrium reactor temperature. The simulation-predicted equilibrium temperature from the gasification process facilitates deriving qualitative findings regarding the gasification reaction. The simulation findings show a progressive increase in methane composition as the oxygen/steam content rises. The high temperature and high methane concentration at lower oxygen/steam-to-PET ratios results from methanation and oxidation reactions [18]. At approximately 4*kg/h* of the gasification agent, there was a sharp decrease in the mass fraction of the syngas ($CO + H_2$). Studies have shown that this implication results from the increased mass fraction of the gasification agent. However, when the gasification agent-to-PET decreases below the threshold, the production of the syngas with other gaseous products will also fall [36].

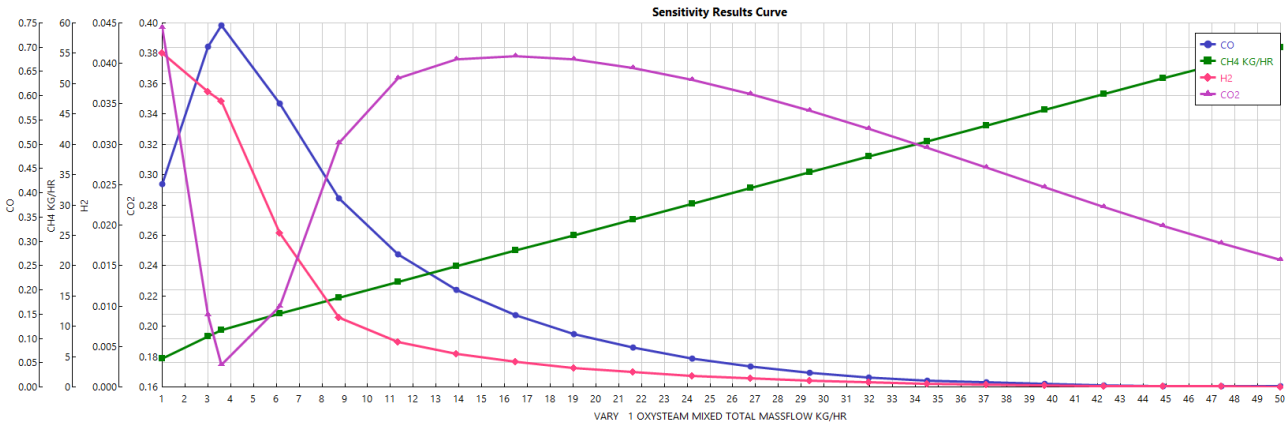

Figure 2: Graphical representation of product mass fraction at various oxygen/steam-to-PET ratios.

Lastly, the calculations for equilibrium in the proposed results are within a reasonable range. However, no experimental literature about the presented work, the gasification of PET using

oxygen/steam as the gasification agent for syngas, investigates the same parameters as the present work.

3.3.3. Feed mass flow rate

This report provided a sensitivity analysis of the mass flow rate (MA) of PET fed into the gasifier and its effect on the composition of the syngas. In addition, the impact of MA on the efficiency of syngas was investigated. Figure 5 illustrates the variability in the gasifier output at various MA. Figure 16 shows that from 3*kg/hr*, CH_4 witnessed an exponential increase to 50*kg/hr*, producing approximately 0.7. The most significant CO yield was produced at a MA of 5*kg/h*. It has been demonstrated conclusively that the exponential growth of the carbon monoxide mass fraction coincides with the steady growth of the feed. At 5*kg/hr*, the mass fraction will steadily decrease until it reaches 0.250.

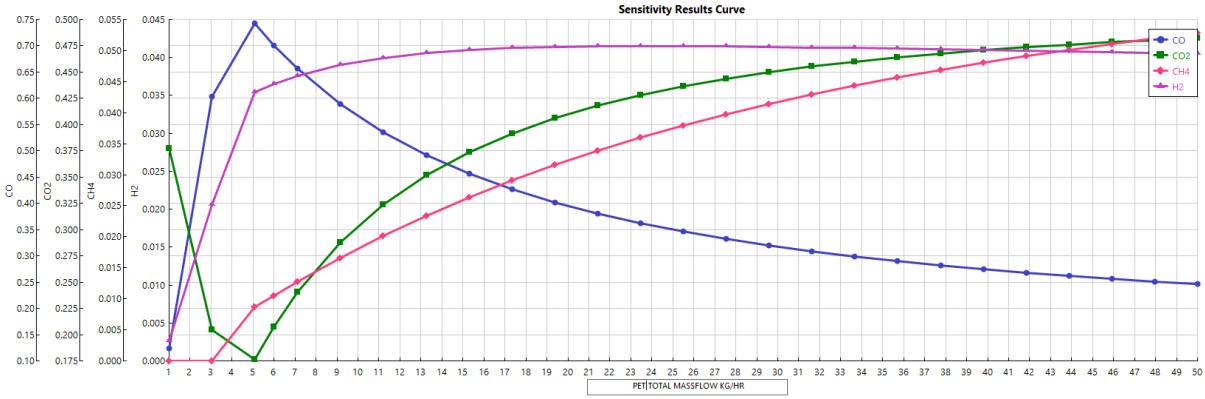

Figure 5: Effect of PET MA on syngas, CO_2, and CH_4 composition.

3.4. Composition

Table 1 depicts the product's composition at different temperatures to highlight the variation in the concentration of gas components at 1 *atm* of pressure. At equilibrium circumstances, various scholars remark that the product gas production increases linearly with temperature [12]. The influence of DRIER temperature on the product composition was determined by varying its temperature.

Table 1. Gasified products at various temperatures.

Temperature	**383,15K**	**483,15K**	**583,15K**	**683,15K**

	Mass fraction	Mass fraction	Mass fraction	Mass fraction
H_2	0.036492	0.036724	0.036988	0.037278
CH_4	0.010511	0.009992	0.009395	0.008737
CO	0.701281	0.719483	0.740459	0.763553
CO_2	0.207553	0.19262	0.175385	0.156388
O_2	$4.30*10^{-6}$	$5.24*10^{-6}$	$6.60*10^{-6}$	$8.61*10^{-6}$
H_2S	0	0	0	0
H_2O	0.044163	0.041182	0.037773	0.034045

Table 1 shows that at equilibrium conditions, the temperature for PET decomposition continues to increase in the DRIER as it progresses from left to right. As a result, the product yield of the syngas ($CO + H_2$) will continue to increase as other products decrease.

4. Process Economics

The economic analysis has been performed to take the unit cost of syngas and assess the overall profitability of the process. To accomplish this calculation, the validated pilot plant from section 3.1. has been scaled from 6kg/h to 60,000 kg/h (525,600 metric tonnes/year), which was the calculated value for the plant capacity, and the costing calculation has been performed based on a large scale. The scale-up was done to increase the product output of the design volume similar to that of an industrial production capacity.

4.1. Capital Expenditure (CAPEX)

The initial step of the design's economic evaluation involved calculating the plant's CAPEX. The CAPEX are cash or credit payments that reflect the initial cost of the plant construction, including engineering, contingency, and unit operations costs. The CAPEX includes the Inside battery limits (ISBL), offsite battery limits (OSBL), engineering and construction costs, and contingency expenses [41]. The ISBL exemplifies the cost of the plant itself, including the purchase and installation of unit operations. To estimate the ISBL, the following Bridgewater correlation was used to calculate the ISBL [41].

$$C = 3200N\left(\frac{Q}{S}\right)^{0.675} \qquad Eqn.(12)$$

Where Q≥ 60,000

C: The ISBL in USD based on US Gulf Coast 2000.

N: The number of unit operations for this plant is 4.

S: The reactor conversion, found to be 0.634.

Q: The plant capacity is 60,000*kg/hr (*525,600 *metric tonnes/year).*

The calculation above generated an ISBL of $126,544,154. The cost escalation index is from the Chemical Engineering Journal—Chemical Engineering Plant Cost Index (CEPCI). The CEPCI value published for 2000 is 394.1, and for the year 2022 is 797.6 [4].

$$\text{Cost in year A} = \text{Cost in year B x } \frac{(\text{Cost index year A})}{(\text{Cost index year B})} \qquad \textit{Eqn. (13)}$$

The CE are index values (dimensionless) used to escalate cost estimates from one-time reference to another to account for inflation. Therefore, the current ISBL for 2022 was then updated to $256,106,615.7. Since the plant location is in the United Kingdom (UK), the equation has to account for this instead of the US Gulf Coast on a 2000 basis for the location factor. The factor for the US Gulf Coast is 1.00, and for the UK, it is 1.02. Hence, the ISBL will be $261,228,748 after accounting for the productivity calibration for the UK at 1.02. Finally, $261,228,748 will equal £207,646,813.35 at 0.79 dollars to Great British Pounds (GBP) conversion.

Table 2. Total capital investment summary (CAPEX).

Cost Parameters	**Cost (GBP)**
ISBL	£207,646,813.35
OSBL (40% of ISBL). *	£83,058,725.34
Engineering and Construction Cost [10% of the direct capital cost (ISBL + OSBL)]. *	£29,070,553.87
Contingency Charges [10% of the direct capital cost (ISBL + OSBL)]. *	£29,070,553.87
Fixed Capital Cost (ISBL + OSBL + engineering cost + contingency cost). *	£348,846,646.43
Working Capital [15% of the direct capital cost (ISBL + OSBL)]. *	£43,605,830.80
Start-Up Expense [10% of the direct capital cost (ISBL + OSBL)]. *	£29,070,553.87
Total Capital Investment [fixed capital cost, working capital, and start-up expense]. *	**£421,523,031.10**

*The percentage values for the CAPEX calculation [41].

Annualised CAPEX will be obtained as the total CAPEX multiplied by the capital recovery factor (CRF) [24], which is calculated by Equation 14 [27].

$$CRF = \frac{i(i+1)^n}{i(i+1)^n+1} \qquad \textit{Eqn. (14)}$$

where is the economic life of the plant and is the interest rate. It is assumed a project life of 25 years and 12% interest rate [25]. Therefore, the annualised CAPEX of production for the plant will be £47,772,620.25 at a CRF of 0.113333357.

4.2. Operating Expenditure (OPEX)

OPEX can be divided into two categories: variable production costs and fixed production costs. Friedli & Bellm (2013) also classified OPEX as either fixed or variable [11].

4.2.1. Fixed Operating Expenditure (FOPEX)

The FOPEX are expenses that are unaffected by the plant's output. Therefore, this expense does not vary with production. The fixed costs include labour and supervision, overhead expenses, maintenance, land rental, environmental fees, and any license or royalties [41]. The FOPEX will be calculated by Equation (15)

$$FOPEX = 0.03\ X\ CAPEX \qquad Eqn.(15)$$

4.2.2. Variable Operating Expenditure (VOPEX)

The VOPEX are those costs that are impacted by fluctuation in plant activity. This includes raw materials, utilities, selling prices, energy consumption, and waste disposal [41].

Table 3. Summary of the Variable Operating Expenditure

Cost Parameters	Cost (£)
Raw materials	£189,448,166.37
Utilities (20% of Revenue) *	£51,311,855.18
Consumables (35% of Revenue) *	£89,795,746.57
Effluent disposable (10% of Revenue) *	£25,655,927.59
Packaging and shipping (10% of Revenue) *	£25,655,927.59

*The percentage values for the cost parameters for the VOPEX estimation [49].

The PET feedstock, oxygen, and water are the materials that will be charged for. It was assumed that the scrap value for the PET feedstock will cost £360/tonne[50], which is equivalent to £189,360,000 for the required plant capacity of 525,600 *metric tonnes/year* (60,000kg/hr).

Table 4. Raw Material Costs.

Material	Price ($/kg)	Mass Flow (kg/yr)	Total Cost ($/year)	Total Cost (£/year) $1 = £0.79	References
Oxygen	2.59	17,520	45,377	35,847.83	[1]
Water	1.26	52,560	66,226	52,318.54	[29]

Therefore, the cost of the raw material will be £189,448,166.37. The Revenue was estimated as the cash flow generated by the sale of the syngas and its byproducts, assuming that their purity meets the required standards. Table 4 summarises the prices of the products generated.

Table 5. Product Sale Prices.

Material	Price ($/kg)	Price ($/Tonnes)	Mass Flow (6 kg/h)	Mass Flow (60,000 kg/h = 525,600 *metric tonnes/year)*	Total Selling Price ($/year)	Total Selling Price (£/year)	References
Hydrogen	3.5	3500	0.3019	26446.44	92,562,540	73,124,406.60	[8]
Carbon monoxide	0.38	380	5.8009	508158.84	193,100,359	152,549,283.6	[19]
Carbon dioxide	0.185	185	1.7169	150400.44	27,824,081	21,981,023.99	[2]
Methane	1.48	1480	0.08694	7615.944	11,271,597.12	8,904,561.72	[15]

The Revenue for this process setup is estimated by multiplying the price by the number of units sold. This is the cash flow generated by the sale of a specific level of output. It was assumed that the products, including the syngas, were all sold. Hence, the sum of the product revenue accumulated from the projected sale of each product will amount to £256,559,275.92.

The location of the gasification plant facility is the United Kingdom. Hence, the profit generated is subjected to UK corporation tax set at 19%. The Corporation tax is the direct tax that a limited corporation must pay. The tax accumulated for the running

of the plant will be calculated by multiplying the corporation tax rate by the taxable income. The following equation was used to calculate taxable income [41]:

$$Taxable\ Income = Revenue - tax\ allowance \qquad Eqn.\ (16)$$

The annual depreciation allowance (ADA) can estimate the tax allowance. This is the untaxed profit. The Equation below illustrates how the ADA and taxable income were derived.

$$ADA = \frac{FCI - SV}{N} \qquad Eqn.(17)$$

The FCI is the fixed capital investment, SV is the scrap value, and N (25 years) is the lifetime of the plant. The scrap value is less than 10% of the ISBL[41]. For this project, it was assumed to be 8.5% of the ISBL. This method will assist in the total generation of the tax accumulated for the running of the plant, which will be £42,678,526.04.

The Payback period (PBP) indicates the time it will take for this investment to reach a break-even point. This will be estimated with the following equation below:

$$PBP = \frac{CAPEX}{\text{Cash Flow per Annum}}$$

The Cash flow per annum is calculated by subtracting the sum of the Annualized OPEX and the total tax accumulated for the running of the plant from the Revenue. The PBP for the investment will be estimated to be approximately 2.5 years.

The return on investment (ROI) for the lifespan of the plant can be evaluated before or after taxes. The ROI illustrates to investors the effectiveness of a particular asset [26]. This can be estimated with the formula below:

$$ROI = \frac{\text{Net cash flow per annum}}{\text{capital cost of the project}}\ x\ 100\% \qquad Eqn.18$$

The ROI calculated has a positive return of 40.1 per cent yearly, meaning that the investment gains compare favourably to the project's cost (i.e., the business is profitable). The cumulative cash flow diagram below shows when the plant would break even and start making a profit. This gives a rough estimate of the plant's profit based on the cumulative cash flow before the discounting factor is used. The cumulative cash flow is the sum of each year's cash flows.

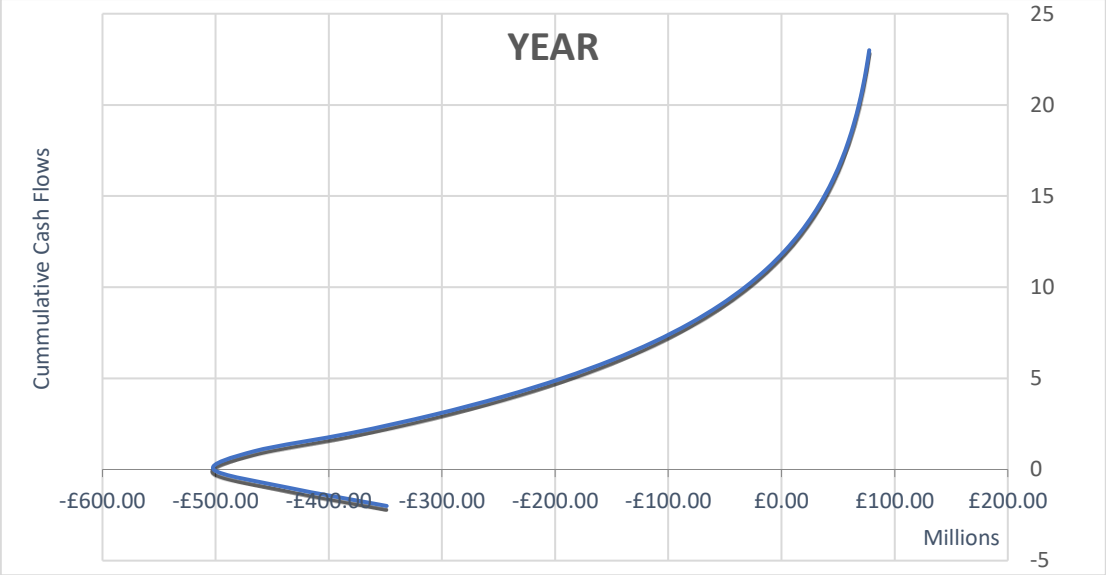

Figure 3: Cumulative cash flow graph for conversion process of PET feed rate to syngas at a 6kg/h feed rate.

Figure 6 represents a graphical presentation of the cumulative cash flow. This chart is made so that the economic projection of the project can be looked at clearly. In addition, the graph illustrates the fixed and working capital investments that were used up before the commencement of production. This chart also analyses the duration it will take for the investment to break even.

The NPV will be used to estimate the operation's cash inflow and outflow and apply the money's time value to determine the likelihood that an investment will generate a profit or a loss [5, 41]. Equation 19 below was proposed by Towler and Sinnott (2019) for estimating the NPV of an investment:

$$NPV = \sum_{n=0}^{n=t} \frac{CF_n}{(1+i)^n} \qquad Eqn.\,(19)$$

Where CF_n is the cash flow in the year n, t is the project life in years, i is the discount factor.

The discount factor was worked out, and the result is rounded to 1.205

5.0. Conclusion

The study investigated the energy generation potential, economic viability, and sustainability of gasification technologies for converting PET waste. It was designed using an equilibrium model of a steady-state process with a continuous flow that predicts the behavioural patterns of the PET gasification process under different operating conditions. The gasification parameters and their flow rate were optimised to achieve the optimal temperature for producing product gas with a high calorific value. In comparison to PE, the percentage values for Ash and hydrogen in the proximate analysis of PET were low (0 and 4.21,

respectively). This input had a significant impact on the Ash and hydrogen contents of the product gas, as it directly affected the feedstock higher heating value (23.34MJ/kg) and lower heating value (10.63MJ/kg) of the PET. However, the product gas composition was optimised by varying the steam flow rate. The Aspen Plus simulation results indicated that the model could predict the effect and individual fractional efficiencies of the PET gasification conversion process. The model did not generate any solid or liquid in the product due to the assumption that the present work made. Therefore, it was determined; however, that product contains many volatile substances.

The economics of the process took into account the economic assessment of the plant as a whole. The capital cost and operational expenses were determined. The result showed that the plant would break even within the first three years, demonstrating its economic viability, with an NPV of £77,574,506.37 and an ROI of 40.1% within the proposed 25 years of running the plant.

The remarkable adaptability of the fluidised bed gasifier suggests it is likely the dominant reactor for gasifying plastic wastes with a high heating value. However, the effects of catalyst performance on process efficiency must be considered. In addition, the study of the kinetics of PET plastic is also essential for the design of processes.

Data availability statement.

The authors confirm that the data supporting the findings of this study are available within the article.

Disclosure statement.

The authors report there are no competing interests to declare.

References

1. Adhikari, B., Orme, C. J., Klaehn, J. R. & Stewart, F. F. (2021) Technoeconomic analysis of oxygen-nitrogen separation for oxygen enrichment using membranes. Separation and

Purification Technology, 268 118703.

2. Ashworth, J. (2022) National history museum. Available online: https://www.nhm.ac.uk/discover/news/2022/september/cost-carbon-dioxide-four-times-higher-than-thought.html [Accessed 15 February 2023].

3. Bai, B., Liu, Y., Zhang, H., Zhou, F., Han, X., Wang, Q., & Jin, H. (2020). Experimental investigation on gasification characteristics of polyethylene terephthalate (PET) microplastics in supercritical water. *Fuel*, *262*, 116630. https://doi.org/10.1016/j.fuel.2019.116630.

4. CEPCI (2022) The chemical engineering plant cost index. Available online: https://www.chemengonline.com/pci-home . [Accessed 30/08/2022]

5. Chae, S. Y., Lee, S. Y., Han, S. G., Kim, H., Ko, J., Park, S., Joo, O., Kim, D., Kang, Y. & Lee, U. (2020) A perspective on practical solar to carbon monoxide production devices with economic evaluation. Sustainable Energy & Fuels, 4 (1), 199-212.

6. Channiwala, S. A. & Parikh, P. P. (2002) A unified correlation for estimating HHV of solid, liquid and gaseous fuels. Fuel, 81 (8), 1051-1063.

7. Chattopadhyay, J., Pathak, T. S., Srivastava, R. & Singh, A. C. (2016) Catalytic co-pyrolysis of paper biomass and plastic mixtures (HDPE (high density polyethylene), PP (polypropylene) and PET (polyethylene terephthalate)) and product analysis. Energy, 103 513-521.

8. Do, T. N., Kwon, H., Park, M., Kim, C., Kim, Y. T. & Kim, J. (2023) Carbon-neutral hydrogen production from natural gas via electrified steam reforming: Techno-economic-environmental perspective. Energy Conversion and Management, 279 116758.

9. Devon County Council (2022) Resource and waste management strategy for devon and torbay 2020 – 2030. Available online: https://refworks.proquest.com/library/62bca3dd8f08f580892661a9/ . [Accessed 27/08/2022].

10. Fivga, A. & Dimitriou, I. (2018) Pyrolysis of plastic waste for production of heavy fuel substitute: A techno-economic assessment. Energy, 149 865-874.

11. Friedli, T. & Bellm, D. (2013) OPEX: A definition. In Anonymous Leading pharmaceutical operational excellence. Springer, 7-26.

12. Fuchs, J., Schmid, J. C., Müller, S., Mauerhofer, A. M., Benedikt, F. & Hofbauer, H. (2020) The impact of gasification temperature on the process characteristics of sorption enhanced reforming of biomass. Biomass Conversion and Biorefinery, 10 (4), 925-936.

13. Gagliano, A., Nocera, F., Bruno, M. & Cardillo, G. (2017) Development of an equilibrium-based model of gasification of biomass by aspen plus. Energy Procedia, 111 1010-1019.

14. Geyer, R., Jambeck, J. R. & Law, K. L. (2017) Production, use, and fate of all plastics ever made. *Science Advances*, 3 (7), e1700782.

15. *Global petrol prices.* (2022) Available. online: https://www.globalpetrolprices.com/methane_prices/ [Accessed 15 September 2022].

16. Hasanzadeh, R., Mojaver, P., Azdast, T., Chitsaz, A. & Park, C. B. (2022) Low-emission and energetically efficient co-gasification of coal by incorporating plastic waste: A modelling study. Chemosphere, 299 134408.

17. Honus, S., Kumagai, S., Fedorko, G., Molnár, V., & Yoshioka, T. (2018). Pyrolysis gases produced from individual and mixed PE, PP, PS, PVC, and PET—Part I: Production and physical properties. *Fuel*, *221*, 346–360. https://doi.org/10.1016/j.fuel.2018.02.074.

18. Kannan, P., Al Shoaibi, A. & Srinivasakannan, C. (2013) Energy recovery from co-gasification of waste polyethylene and polyethylene terephthalate blends. Computers & Fluids, 88 38-42.

19. Kildahl, H., Wang, L., Tong, L., Cao, H. & Ding, Y. (2022) Industrial carbon monoxide production by thermochemical CO2 splitting – A techno-economic assessment. Journal of CO2 Utilization, 65 102181.

20. Kumar, A. & Samadder, S. R. (2017) A review on technological options of waste to energy for effective management of municipal solid waste. *Waste Management*, 69 407-422.

21. Lee, J., Lin, K. A., Jung, S. & Kwon, E. E. (2022) Hybrid renewable energy systems involving thermochemical conversion process for waste-to-energy strategy. *Chemical Engineering Journal*, 139218.

22. Lee, K.-H., & Shin, D.-H. (2007). Characteristics of liquid product from the pyrolysis of waste plastic mixture at low and high temperatures: Influence of lapse time of reaction. *Waste Management*, *27*(2), 168–176. https://doi.org/10.1016/j.wasman.2005.12.017.

23. Mahinpey, N., & Gomez, A. (2016). Review of gasification fundamentals and new findings: Reactors, feedstock, and kinetic studies. *Chemical Engineering Science*, *148*, 14–31. https://doi.org/10.1016/j.ces.2016.03.037.

24. McCollum, D. L. & Ogden, J. M. (2006) Techno-economic models for carbon dioxide compression, transport, and storage & correlations for estimating carbon dioxide density and viscosity.

25. McCoy, S. T. & Rubin, E. S. (2008) An engineering-economic model of pipeline transport of CO2 with application to carbon capture and storage. International Journal of Greenhouse Gas Control, 2 (2), 219-229.

26. Menezes, M. B., Kim, S. & Huang, R. (2015) Return-on-investment (ROI) criteria for network design. European Journal of Operational Research, 245 (1), 100-108.

27. Mores, P., Rodríguez, N., Scenna, N. & Mussati, S. (2012) CO2 capture in power plants: Minimization of the investment and operating cost of the post-combustion process using MEA aqueous solution. International Journal of Greenhouse Gas Control, 10 148-163.

28. Motta, I. L., Miranda, N. T., Maciel Filho, R. & Maciel, M. R. W. (2018) Biomass gasification in fluidized beds: A review of biomass moisture content and operating pressure effects. Renewable and Sustainable Energy Reviews, 94 998-1023.

29. NUMBEO (2022) *Price rankings by country of water (1.5 liter bottle) (markets).* Available online: https://www.numbeo.com/cost-of-living/country_price_rankings?itemId=13. [Accessed 24/09/2022]

30. Olofsson, F. & Halvarsson, H. (2020) Small scale energy conversion of plastic waste: Identification of gasification process parameters through modelling in aspen plus.

31. Onwudili, J. A., Insura, N., & Williams, P. T. (2009). Composition of products from the pyrolysis of polyethylene and polystyrene in a closed batch reactor: Effects of temperature and residence time. *Journal of Analytical and Applied Pyrolysis*, *86*(2), 293–303. https://doi.org/10.1016/j.jaap.2009.07.008

32. Paula, C.,Pinto, F., Ramos, A. M.,Gulutlu, I., cabrita, I., Bernardo, M. S. (2010). Study of the Pyrolysis Kinetics of Mixture of Polyethylene, Polypropylene and Polystyrene.

33. Plus, A. (2000) Getting started modeling processes with solids. Version L 0.2. Aspen Technology Inc., Cambridge, USA.

34. Pohořelý, M., Vosecký, M., Hejdová, P., Punčochář, M., Skoblja, S., Staf, M., Vošta, J., Koutský, B. & Svoboda, K. (2006) Gasification of oal and PET in fluidized bed reactor. Fuel, 85 (17-18), 2458-2468.

35. Saad, J. M. & Williams, P. T. (2016) Catalytic dry reforming of waste plastics from different waste treatment plants for production of synthesis gases. *Waste Management,* 58 214-220.

36. Sikarwar, V. S., Zhao, M., Fennell, P. S., Shah, N. & Anthony, E. J. (2017) Progress in biofuel production from gasification. Progress in Energy and Combustion Science, 61 189-248.

37. Statista (2022) *Annual production of plastics worldwide from 1950 to 2020(in million metric tons).* Available online: https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/ . [Accessed 25/08/2022].

38. Sundararajan, T., Raghavan, V., Ajilkumar, A. & Kumar, K. V. (2017) Mathematical modelling of coal gasification processes. IOP Conference Series: Earth and Environmental Science. IOP Publishing.

39. Tavares, R., Ramos, A., & Rouboa, A. (2018). Microplastics thermal treatment by polyethylene terephthalate-biomass gasification. *Energy Conversion and Management*, *162*, 118–131. https://doi.org/10.1016/j.enconman.2018.02.001.

40. Touhami, D., Zhu, Z., Balan, W.S., Janaun, J., Haywood, S., Zein, S. Characterization of rice husk-based catalyst prepared via conventional and microwave carbonization. J. Environ. Chem. Eng., 5 (2017), pp. 2388-2394.

41. Towler, G., Sinnott R., 2019, *Chemical Engineering Design : SI Edition*, Elsevier.

42. Ward, J., Rasul, M. G. & Bhuiya, M. (2014) Energy recovery from biomass by fast pyrolysis. Procedia Engineering, 90 669-674.

43. Webb, H. K., Arnott, J., Crawford, R. J., & Ivanova, E. P. (2013). Plastic Degradation and Its Environmental Implications with Special Reference to Poly(ethylene terephthalate). *Polymers*, *5*(1), 1–18. https://doi.org/10.3390/polym5010001.

44. Xu, J., Yu, J., Xu, J., Sun, C., He, W., Huang, J. & Li, G. (2020) High-value utilization of waste tires: A review with focus on modified carbon black from pyrolysis. *Science of the Total Environment,* 742 140235.

45. Yansaneh, O.Y.; Zein, S.H. Latest Advances in Waste Plastic Pyrolytic Catalysis. Processes

2022b, 10, 683. https://doi.org/10.3390/pr10040683.

46. Yansaneh, O.Y.; Zein, S.H. Recent Advances on Waste Plastic Thermal Pyrolysis: A Critical Overview. Processes 2022a, 10, 332. https://doi.org/10.3390/pr10020332.

47. Zein, S. H., Grogan, C. T., Yansaneh, O. Y., & Putranto, A. (2022). Pyrolysis of High-Density Polyethylene Waste Plastic to Liquid Fuels—Modelling and Economic Analysis. Processes, 10(8), Article 1503. https://doi.org/10.3390/pr10081503.

48. Zein, S. H., Hussain, A. A., Yansaneh, O. Y., & Jalil, A. (2022). Modelling and Simulation of Dissolution/Reprecipitation Technique for Low-Density Polyethene Using Solvent/Non-Solvent System. Processes 2022, 10(11), 2387; https://doi.org/10.3390/pr10112387

49. Zein, S. H. & Antony, A. (2022) Techno-economic analysis and feasibility of industrial-scale activated carbon production from agricultural pea waste using microwave-assisted pyrolysis: A circular economy approach. Processes, 10 (9), 1702.

50. Zest (2023) Zest recycle. Available online: https://www.zestrecycle.co.uk/prices/ [Accessed 09 June, 2023].