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Steam gasification modeling of polyethylene (PE) and polyethylene terephthalate (PET) wastes: A case study

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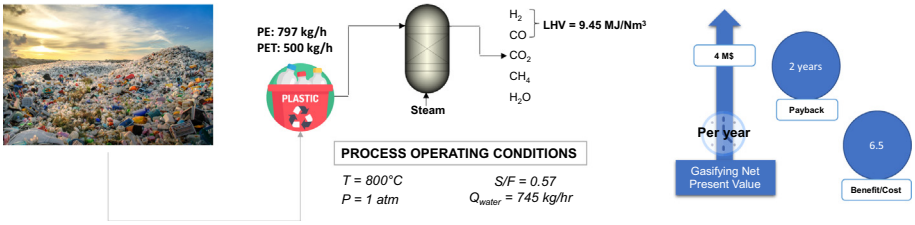
HIGHLIGHTS

- Adding PET to the input feed does not increase the syngas yield in the products.
- Syngas LHV of 9.45 MJ/Nm^3 is achievable at operating conditions of 800 °C, 1 atm.
- Steam to feed ratio of 0.57 produces the optimum amounts of syngas.
- For such a process, the initial investment can be returned within 2 years.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper is the first to study the effect of adding PET, separator, and financials on a PE steam gasification plant based in Lebanon. The main aim is to shed light on the possibility of valorizing plastic wastes while reducing the environmental impact of landfilling and creating benefits. Using Aspen Plus, a plant that can turn plastic waste into syngas is designed and modeled. PE and PET model inputs of 797 and 500 kg/hr, respectively, were chosen based on Lebanese data. The addition of PET did not significantly improve the mole fractions of the end product when compared with PE only as an input feed. The final optimum conditions of this model were chosen based on sensitivity analyses of different parameters. There were concluded to be a temperature of 800 °C, pressure of 1 atm, Steam/Feed mass ratio of 0.57, water flowrate of 745 kg/hr, and syngas LHV of 9.45 MJ/Nm^3. Calculations showed a total Net Present Value 6 times larger than the initial investment and a Payback Period of 2 years by implementing the model. Although based on a Lebanese case study, this research will urge the establishment of sustainable waste and financial policies in countries facing the same issues.

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1. Introduction

The term plastic is used for any synthetic or semi-synthetic polymer. Plastic refers to the ability to deform without breaking (plasticity), low conductivity, low density, toughness, and transparency (Plastic, 2022). Such valuable properties allow plastics to be extensively produced by well-known chemical industries like BASF and heavily used in various sectors such as packaging, textiles, and industrial machinery. However, despite its convenience in humans' daily lives, plastic causes significant environmental harm. Being very stable against degradation, plastic waste has become an apparent problem threatening landfills and aquatic life due to pollution. It is even estimated that by 2050, more plastic than fish will be in the oceans (Wearden, 2050). Moreover, microplastics are now capable of reaching our nutritious intake

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Abbreviations

WTE	Waste-to-Energy
PP	Polypropylene
PVC	Polyvinylchloride
PE	Polyethylene
PET	Polyethylene Terephthalate
IBC	International Business Consultants
LHV	Low Heating Value
S/F	Steam to Feed Ratio
MSW	Municipal Solid Waste
CAPEX	Capital Costs
OPEX	Operating Costs
NPV	Net Present Value
IRR	Internal Rate of Return
BCR	Benefit to Cost Ratio
PBP	Payback Period

not only through marine life but also through the soil and crops (Huang et al., 2021).

Plastic demand is continuously increasing due to the increase in the human population. As a result, annual plastic production had escalated from 1.5 million metric tons in 1950 to 359 billion metric tons in 2018, 9 % of which have been recycled, 12 % incinerated, and 79 % released to the environment or stored in landfills (Oa and Oa). Worldwide, the cumulative plastic production has exceeded eight billion metric tons. China is the largest producer of plastics, with around 29 %, after which Europe and North America have shares of 19 % and 18 %, respectively (d'Ambrières, 2019).

Undesired consequences of essential plastic use have driven engineers to think of ways to reduce plastics' adverse environmental effects. One such practical way was the introduction of the reduce, reuse, and recycle mindset (Gunda et al., 2016). Recycling is the most feasible option since it allows for the use of plastic, hence not depending on altering consumer habits, yet converting plastic waste to other valuable products. It can be considered an industrial-scale process, even though it can be done at home on a small scale. The sustainability of the process depends primarily on whether the plastic usage cycle is closed or not.

Utilizing energy recovery from the incineration of plastic waste is a straightforward way to replace fossil fuels in heating and power applications. Burning plastics, however, causes more net CO_2 emissions because they are petrochemical products. Therefore, it is not advantageous to recover energy from the incineration of plastic owing to concerns about global warming (Li et al., 2021).

The chemical recycling of plastics was the focus of the study. The latter includes using high temperatures and/or catalysts to chemically change plastic structure and constituents. Chemical recycling is desirable since it can increase plastic recycling rates by converting mixed plastic waste, unlike mechanical recycling (Oasmaa, 2019). Furthermore, using such chemical recycling is highlighted in the newly developed Waste-to-Energy (WTE) process. The latter uses plastics' high carbon and hydrogen content by converting them into valuable hydrocarbons like diesel oils, methanol, synthetic oils, synthesis gas, etc. (Khan et al., 2016).

In addition to hydrogen and carbon monoxide, synthesis gas, also known as syngas, includes small amounts of carbon dioxide and other gaseous traces. It is an essential feedstock for producing chemicals like fertilizers, fuels, solvents, and synthetic materials (What is SynGas, 2013.).

Multiple methods can do the conversion process of plastic waste to syngas. These include pyrolysis-catalytic dry reforming, air gasification, steam gasification, co-gasification, etc. Different operating conditions, reactor designs, catalysts, syngas heating values, and syngas yields are the factors that will determine the choice of the conversion process model. According to the literature, pyrolysis-catalytic dry reforming (Saad and Williams, 2017; Mohammed et al., 2019) takes mixed plastics as an input, operates at temperatures between 800 and 850 °C, and can produce up to 132 mmol of syngas/g. However, air gasification works on Polypropylene (PP) at lower temperatures (Sancho et al., 2008; Xiao et al., 2007). Steam gasification's input varies between Polyvinylchloride (PVC), mixed plastics, Polyethylene (PE), and PE + PP and can produce syngas with heating values up to 25 MJ/m^3 (He et al., 2009; Saebea et al., 2020). Finally, co-gasification blends the plastic input with biomass and operates at temperatures between 800 and 900 °C. As a result of the identical intended products for all feedstocks, gasification also has the advantage of being more adaptable in treating various composite feedstocks. Therefore, it can also be incorporated into existing energy systems and fuel production (Lopez et al., 2018; Pereira et al., 2012).

Plastic disposal has always been a significant concern due to pollution and its effects on humans, animals, and the environment. Especially after the COVID-19 pandemic, illegal and harmful plastic disposal issues increased dramatically (Patrício Silva et al., 2021). In Lebanon, there is no efficient disposal system that can handle both organic and plastic waste. For this, the paper's main aim was to simulate the applicability of a sustainable treatment method for plastics in a country lacking efficient management of such waste. To our knowledge, no previous studies tackled plastic treatment in the country. The focus was on managing organic waste and its conversion to bioenergy (El Achkar et al., 2018b; El Achkar et al., 2020; El-Achkar et al., 2017; El Achkar et al., 2018a; El Achkar et al., 2018; El Achkar et al., 2016). The input of the proposed design was extracted from the data of Lebanese recycling companies: International Business Consultants (IBC), Phoenix, and Replast; those companies show the largest share of plastic collection in the country. This study utilizes the steam gasification process to transform Polyethylene (PE) and Polyethylene Terephthalate (PET) plastics into syngas. The process is simulated using Aspen Plus software to study the effect of the process conditions like temperature and pressure, the feed composition, and the addition of a flash separator on the process output. A financial study was conducted to highlight the benefits of implementing such treatment nationally in a country currently suffering from economic and environmental crises.

2. Methodology

2.1. Process description

Fig. 1 illustrates the process flow diagram (PFD) of the gasification of plastics using Aspen Plus simulation software. The plastic wastes chosen in this process are PE and PET due to the abundance in Lebanon. The plastic feed is labeled non-conventional, forcing the pyrolysis before gasification to decompose the plastics into each element before the reaction. Consequently, the gasification process consists of two stages: pyrolysis (PYRO) to decompose the plastic waste and gasifier (GASIFIER), involving the reaction of plastic with steam to produce syngas. Two heaters are present where the first one (HEATER 1) heats the plastic feed before pyrolysis and the second heater (HEATER 2) heats water turning it into

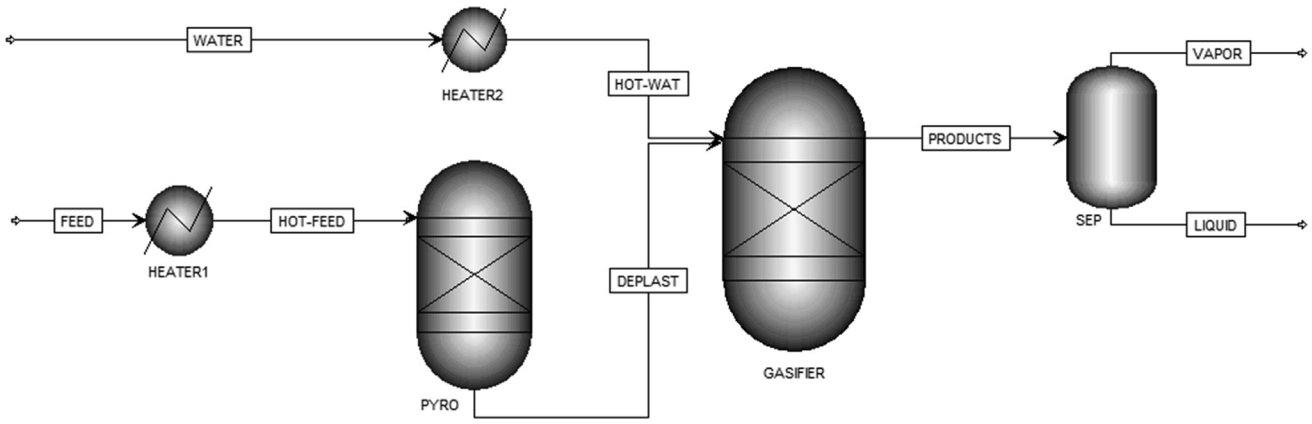

Fig. 1. PFD of Gasification of PE and PET.

steam before entering the gasifier. The decomposed plastics in the pyrolysis unit are fed directly to the gasifier along with steam. A flash separator (SEP) is located after the gasifier in which the products formed after gasification are separated into vapor and liquid. Syngas will be in the vapor form and separated from the liquid phase to have higher composition or purity of syngas.

2.2. Input for simulation

In this work, the thermodynamics calculations were performed using the Aspen Plus simulator, where POLYNRTL was used as the equation of state. The input to the process consists of water (H_2O), hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), polyethylene (PE), polyethylene terephthalate (PET), and coke (C). PE, PET, and coke are non-conventional (NC) materials, while the rest are conventional. As Lebanon was our study case, the simulation was done for 797 and 500 kg/hr input feed for PE and PET, respectively. The last numbers resulted from data collected from Lebanese recycling companies: International Business Consultants (IBC), Phoenix, and Replast.

2.2.1. NC properties

Aspen Plus requires extra inputs to the model to simulate a non-conventional feed. This is because properties such as density, heat capacity, and heat of formation or polymerization change with the environment, weather, operating conditions, etc. According to that, different references were used to get an average of the latter properties (Table 1).

The phase and chemical equilibrium calculations in Aspen Plus do not include non-conventional solids. Non-conventional solids are components without a clear chemical formula as they depend on their origin, formulation conditions, etc. Such solids lack important data for equilibrium and physical properties. They are characterized only by enthalpy and density models (Chemical Process Design and Simulation: Aspen Plus and Aspen Hysys Applications, 2022). The density model is named DNSTYGEN, a general model that gives the density of any non-conventional solid component. However, the enthalpy model is called ENTHGEN, a general model that offers the specific enthalpy of any non-conventional component as a simple mass-fraction weighted average for the enthalpies of its constituents. HCGEN is used for heat capacity and DHFGEN for the heat of formation.

2.2.2. Component attributes

Aspen Plus characterizes non-conventional solids in terms of empirical factors called Component Attributes. The proximate and ultimate analysis described PE, PET, and coke (Table 2). The corresponding results and the standard deviation (SD) are shown in eq. (1). The standard deviations were calculated using the following equation:

$$\sigma = \sqrt{\frac{\sum (x_i - \mu)^2}{N}} \quad (1)$$

Where:
σ = population standard deviation.
N = the size of the population.
x_i = each value from the population.
μ= the population mean.

Significant statistical differences between means at 0.05 % levels were determined according to Tukey's test. Statistical tests were conducted using SPSS (SPSS software, V20, SPSS Inc., Chicago, USA).

3. Results and discussion

3.1. Product gas composition

Shown in Table 3 are the mole flowrates, mole fractions, mass flowrates, mass fractions, volume flowrates, and volume fractions of the separator vapor products. This stream resembles the end of the simulated model, i.e., the products to be collected and sold.

Table 1
Properties of Nonconventional Solids.

	PE (Polymers - Specific Heats, 2022; Density, 2022)	SD	PET (Mishra and Deopura, 1990; Polyethylene Terephthalate Polyester, 2003)	SD	Coke (Ibrahim and Ali, 2004; Al-Haj Ibrahim and Abdullah, 2014)	SD
Density (kg/m^3)	918	58.3	1352.5	42.7	1380	14.1
Heat Capacity (J/kg.K)	1916.7	375.3	1183.3	175.5	1500	–
Heat of Polymerization (kcal/kg)	796.43	–	33.5	–	0	–

Table 2
The proximate and Ultimate Analysis of PE, PET, and Coke used in the Simulation.

	PE (Kannan et al., 2013; Saebea et al., 2020; Umeki et al., 2009)	SD	PET (Optimization of Waste Plastics Gasification Process Using Aspen-Plus, 2022; Kannan et al., 2012; Tavares et al., 2018; Jia et al., 2020)	SD	Coke (Tavares et al., 2018; UENC for E Assessment, 2009; Ibrahim and Ali, 2004; Wang et al., 2004)	SD
Moisture (wt%)	0.016	0.008	0.03	0.047	0.46	0.124
Proximate analysis, wt% dry basis						
Fixed Carbon	0.008	0.016	10.2	1.123	87	2.087
Volatile Matter	99.872	0.060	89.07	0.985	12.016	1.241
Ash	0.12	0.060	0.73	0.964	0.984	0.537
Ultimate analysis, wt% dry basis						
Carbon	85.652	0.326	61.91	0.357	84.426	2.668
Hydrogen	14.074	0.464	4.3	0.101	3.764	0.483
Nitrogen	0.104	0.054	0.06	0.101	1.165	0.213
Chlorine	0	0	0	0	0	0
Sulfur	0.05	0.025	0	0	7.03	1.005
Oxygen	0	0	33	0.358	2.63	2.629

Table 3
Separator Vapor Stream Compositions.

	Mole Flowrate (kmol/hr)	Mole Composition	Mass Flowrate (kg/hr)	Mass Composition	Volume Flowrate (m^3/hr)	Volume Composition
H_2	138.46	0.777	279.12	0.20	3403.92	0.81
CO	20.15	0.113	564.50	0.45	495.18	0.12
CO_2	3.40	0.019	149.56	0.12	75.54	0.02
CH_4	8.76	0.049	140.59	0.10	210.47	0.05
H_2O	7.48	0.041	134.70	0.12	0.14	0.00
Total	**178.25**	**1**	**1,268.47**	**1**	**4,185.25**	**1**

3.2. Model validation

Model validation is necessary to assess the validity of the data obtained from the simulation. Hence, simulated data were compared to experimental data found in the literature. This approach is quite palpable in many studies. The experimental values were obtained from a study by Lopez et al. (Lopez et al., 2015), where only PE was used at 1 atm and 700 °C. Also, the steam-to-feed ratio was 1. Our results for PE steam gasification are therefore compared with the experimental data for validation.

Hydrogen and carbon monoxide compositions showed similar values compared with the experimental results. In this simulation, hydrogen takes 79.82 % by volume of gas, while in the literature, it takes 73.47 % by volume (Lopez et al., 2015). Carbon monoxide composition was 13.47 % and 14.86 % by volume in this study and literature, respectively.

It can be concluded that the model had approximately the same results for carbon monoxide and hydrogen, which are the most important components in the simulation since they represent syngas. Thus, the model is validated for PE steam gasification. This step was done to ensure that the process gives relatively accurate results for the steam gasification of plastics. As a result, it was concluded that PET could also be simulated using the same model. It is essential to mention that no experimental data were found for the same operating conditions the study is working at for steam gasification of PET only, as different studies include mixed plastics. The final results of the simulation will show that the addition of PET does not affect the overall product.

3.3. Parameters analysis

In this section, sensitivity analyses are done to study the effect of changing different parameters on the outcome of the simulations. Aspen output results are set at a confidence level of 95 %, assuming a 5 % deviation. These errors or uncertainties can be seen in all figures in this section.

3.3.1. Effect of adding PET on product mole composition

First, the changes in the volume percentage of gas product composition are presented in Table 4. For reasonable comparison, the results were taken at the same operating conditions: S/F ratio of 1, temperature of 700 °C, and pressure of 1 atm.

Upon adding PET to the feed, the percent volume of hydrogen gas moderately increased. However, no increase in carbon monoxide or methane was observed. Also, there was a rise in the amount of carbon dioxide produced.

Table 4 shows a minor enhancement of the hydrogen molar fraction in the separator vapor product stream. Moreover, carbon monoxide is produced in fewer amounts when PET is present, affecting the volume of syngas produced from the steam gasification process. In summary, the increase in syngas volume was only around 1.3 %, and a slight improvement in syngas' mole fraction in the gasifier product stream was observed. The slight rise of syngas in the product stream with PET as input is generally not worth the time and money spent on the chemical recycling of Lebanon's chosen plastic waste via steam gasification. Moreover, on an industrial scale, PET pyrolysis can release benzoic acid, and the condensed terephthalic acid can result in pipe clogging and corrosive problems (Li et al., 2021).

3.3.2. Effect of separator on low heating value

A considerable amount of water in the gas stream must be removed to increase the syngas heating value. Since the reactions include steam as a reactant, as seen in R1 and R2 (refer to Table 5), it could be expected to have some unreacted steam left at the outlet.

The model was first sampled using a separator to decrease the water content in the gas effluent. The separator model used in the simulation is the "SEP Flash2" which gives two outlet streams.

Table 4
Product Volume Percentages for PE feed compared to feed with PE and PET.

	Gas Composition (% volume)		Product Molar Composition at S/F of 0.574	
	PE only	PE and PET	PE only	PE and PET
H_2	79.82	83.44	0.7285	0.7767
CO	13.47	11.05	0.1257	0.1130
CO_2	2.743	3.620	0.0123	0.0190
CH_4	3.967	1.890	0.0897	0.0491
H_2O	–	–	0.0438	0.0419

Table 5
Reactions considered in the steam gasification model.

Reactions	Reaction name	Standard Enthalpy ($kJ.mol^{-1}$)
$CH_4 + H_2O \leftrightarrow CO + 3H_2$	R1: Steam Reforming	+206
$CO + H_2O \leftrightarrow CO_2 + H_2$	R2: Water Gas Shift	−41
$C_nH_m + nH_2O \leftrightarrow nCO + (m/2 + n)\ H_2$	R3: Higher Hydrocarbons Steam Reforming	+740 ~ +2302

In our case, the input feed was separated into liquid and vapor steams at a temperature of 30 °C and atmospheric pressure.

To assess whether adding a separator is feasible for this process, a comparison between the cost of separator operation with the increase of product composition in its vapor stream was made.

Therefore, the kilowatts required to operate a separator are evaluated and compared with the LHV differences of the product streams. The calculation of the Low Heating Value (LHV) for the vapor stream before and after separation was done since the price of the syngas is highly dependent on the LHV. Eq. (2) is used to calculate the LHV (Saebea et al., 2020):

$$LHV = (y_{CO} \times 12.636) + (y_{H_2} \times 10.798) \quad (2)$$

LHV is the low heating value in MJ/Nm^3, y_{CO} is the carbon monoxide mole fraction in mol/mol, and y_{H2} is hydrogen's mole fraction in mol/mol. The LHV is calculated based on the mole fractions of CO and H_2. First, before separation occurred, simulation results showed y_{CO} = 0.1088 and y_{H2} = 0.7478. Accordingly, the LHV for this syngas equals 9.45 MJ/Nm^3. However, after separation, the mole fraction values increased to y_{CO} = 0.1131 and y_{H2} = 0.7768.

The data resulted in an LHV of 9.82 MJ/Nm^3, which, compared to the LHV before separation, leads to an increase of only 4 %. Simultaneously, the separator needed a heat duty of 1,382 kW. Consequently, adding this massive flashing cost to increase the LHV by an insignificant percentage will not be recommended. This is why, as a result, a separator is not recommended in this model.

3.3.3. Effect of gasifier temperature and pressure on product mole composition

As shown in Fig. 2, the general trend is that as the gasifier temperature increases, the amount of syngas in the process increases, and carbon dioxide, methane, and water decrease. This trend is because the chemical reactions that produce syngas are endothermic, which means they are favored at high temperatures. At the same time, reactions for methane, carbon monoxide, carbon dioxide, and water are exothermic.

The curves in Fig. 3 reflect that Steam Reforming gas products tended to increase with rising temperature. Among these curves, from 750 to 800 °C, the increase in H_2 and CO was remarkable, whereas, for the other temperatures, the gas product mole fractions increased only slightly. The chemical equilibrium could explain this phenomenon. Because the tar reforming reaction (R3) and char steam gasification (R1) are both endothermic processes (refer to Table 5), raising the temperature is likely to cause the equilibrium of the reactions to shift to the right, improving the yields of H_2 and CO. Even though a higher temperature led to the water–gas shift (WGS) reaction (R2) shifting to the left.

When the temperature of the gasifier was 700 °C, the operating temperature in the simulation, the product molar composition constituted of 0.74 hydrogen, 0.11 carbon monoxide, 0.08 water, 0.05 methane, and 0.02 carbon dioxide. As the temperature increased to 800 °C, there was a significant increase in syngas produced. At that temperature, the product molar composition was 0.79 hydrogen, 0.14 carbon monoxide, 0.05 water, 0.01 methane, and 0.01 carbon dioxide. Finally, as the temperature increased from 800 °C to 1100 °C, there was a non-significant change in the product molar composition. From 700 °C to 800 °C, the changes

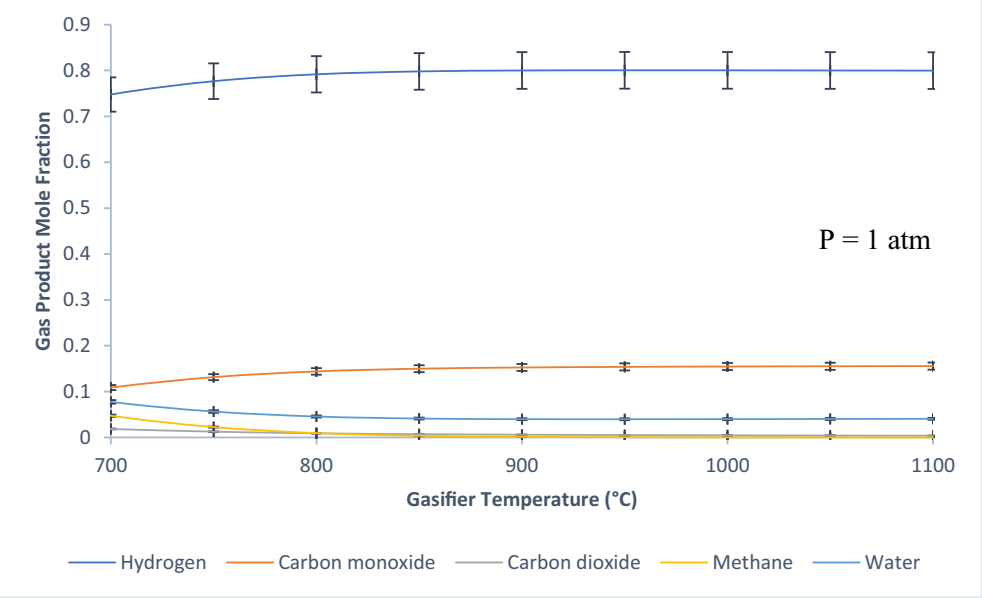

Fig. 2. Effect of Gasifier Temperature on Gas Product Composition.

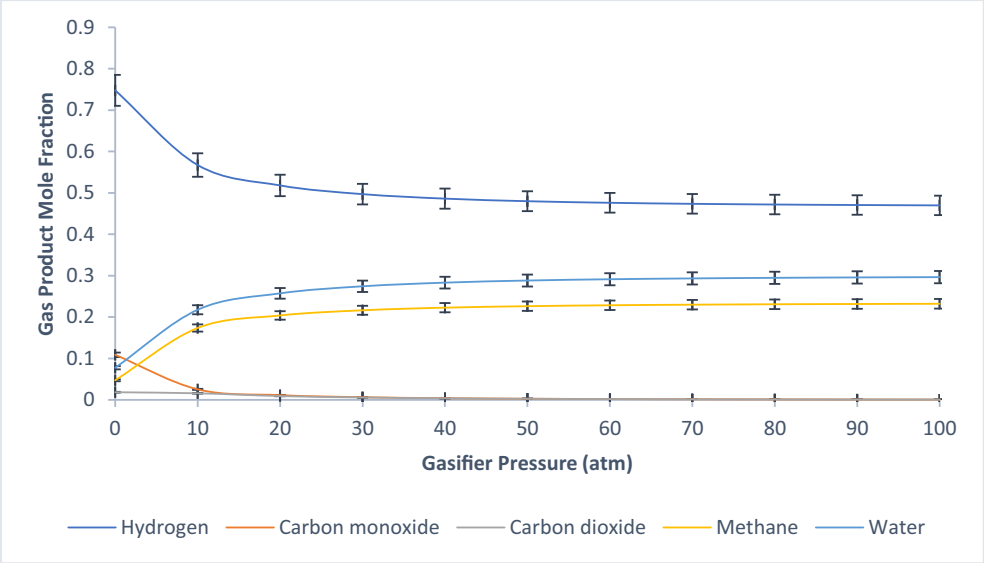

Fig. 3. Effect of Gasifier Pressure on Gas Composition.

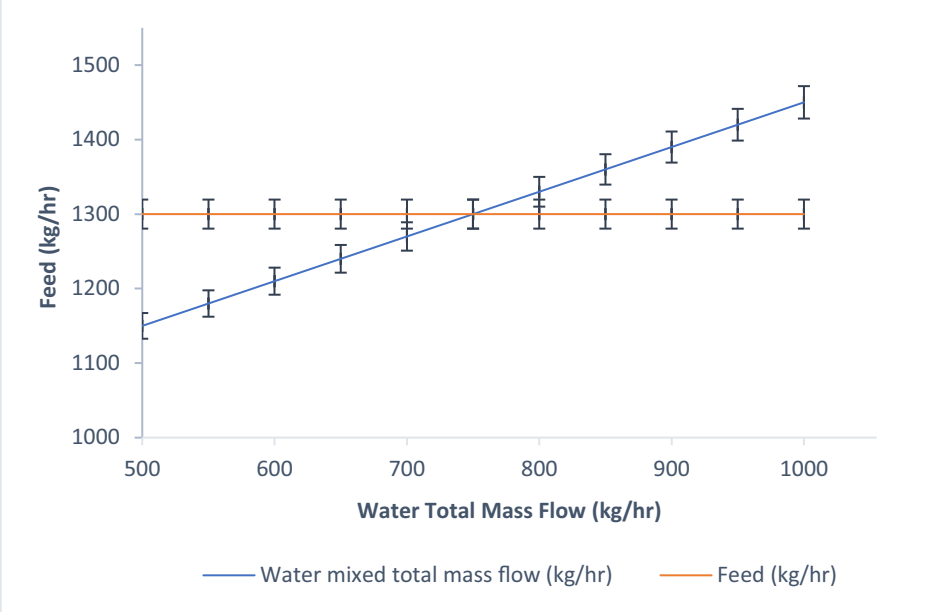

Fig. 4. Determining Water Flowrate by Sensitivity Analysis.

in the gas product mole fractions indicate a significant statistical difference between values at the 0.05 % level, according to Tukey's test. However, it was not the case for mole fractions between 800 °C and 1100 °C. This implies that it is not worth increasing the temperature to 1100 °C since it will cost more money in terms of energy consumption. Consequently, the optimum operating temperature can be set to 800 °C.

Fig. 3 shows the effect of pressure on product composition. This analysis is done to choose the optimum operating conditions for the reactor. The general trend is that as the pressure increases, the amount of syngas and carbon dioxide produced will decrease while methane and water will increase. This trend is due to Le Chatelier's principle, which states that if a system at equilibrium is subjected to an increase in pressure, the system moves to decrease this pressure; the side has a smaller number of mols.

The highest product molar fraction for the syngas was obtained when the pressure was 0 atm, where the hydrogen's composition was 0.75, and that of carbon monoxide was 0.11. The problem is that operating in vacuum conditions requires much equipment and will increase operating costs. Upon operating at atmospheric pressure, the product gas molar composition will be the same as the one mentioned before while running at 700 °C, which is close to that operated at 0 atm. As the pressure increased to 20 atm, a sharp decrease in syngas was produced, while methane and water increased significantly. At that pressure, the product molar composition is 0.52 hydrogen, 0.26 water, 0.2 methane, 0.01 carbon

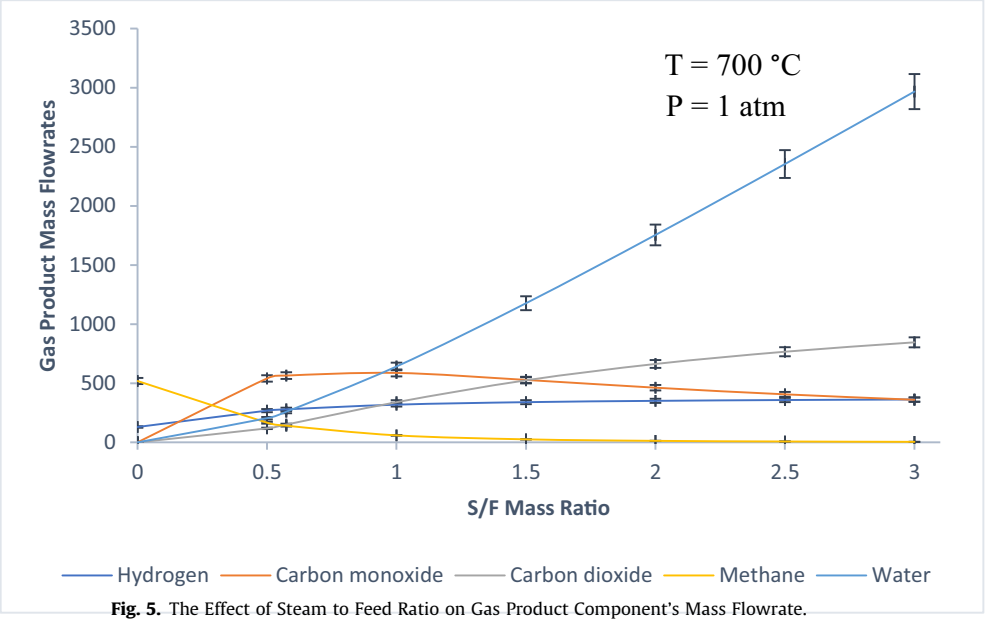

Fig. 5. The Effect of Steam to Feed Ratio on Gas Product Component's Mass Flowrate.

monoxide, and 0.01 carbon dioxide. Finally, the effect of increasing the pressure from 20 to 100 atm was not that significant. Therefore, it is concluded that the optimum operating pressure is 1 atm.

3.3.4. Effect of water flowrate on product mole composition

Optimum water flowrate. In order to determine the optimum flow rate of water needed to be used in the simulation, Fig. 4 was plotted by a sensitivity analysis from ASPEN. This figure shows two curves, mainly the water flowrate in blue and the feed flowrate in green. The optimum steam flowrate is determined where the two curves intersect, and, in this case, the optimum amount of water flowrate to be fed is 745 kg/hr. This water flow rate is equivalent to a steam-to-feed ratio of 0.57, considered the optimum S/F.

Steam to feed ratio. As shown in Fig. 5, the curve's general trend is that as the S/F ratio increases, the amount of hydrogen and carbon dioxide increases, methane decreases, and carbon monoxide increases until it reaches a maximum and decreases. Le Chatelier's principle explains this trend. If a system at equilibrium is exposed to a change in the amount of one reactant, the water here, the system will move in the opposite direction to release the stress.

Again, an increased steam supply can increase H_2 yield via *R*3, WGS reaction R2, and char steam gasification R1 (refer to Table 5). Fig. 5 reveals that hydrogen yield rose slightly while CO formation decreased with a higher S/F ratio, in which the WGS reaction could play an essential role. The same reaction also implies that CO_2 should increase, which was also observed by the curve trend.

As the S/F increased to 0.57, there was a sharp increase in the amount of hydrogen, carbon monoxide, and carbon dioxide produced, reaching 279 kg/hr, 564 kg/hr, and 150 kg/hr, respectively. In contrast, methane decreased sharply until it reached a 140 kg/hr flow rate. Then as the S/F increased from 0.57 to 3, there was no significant change in the hydrogen produced. On the other hand, while water's flowrate increased up to 2966 kg/hr, carbon monoxide and methane's flowrates decreased to 360 kg/hr and 4 kg/hr, respectively. The results from Fig. 5 validate the results from Fig. 4, which state that the optimum S/F is 0.57. Therefore, although operating at a high S/F ratio decreases the tar content in the produced gas, but on the other hand, no significant increase in hydrogen production was seen. Besides, carbon monoxide production will decrease if the steam-to-feed ratio exceeds 1. In addition, the energy needed to heat a large amount of steam is much higher, increasing the operating cost of the process.

The model produced syngas with an LHV of 9.45 MJ/Nm^3 at 800 °C. However, compared with literature data for air gasification of plastic waste, the latter showed LHVs ranging between 6 and 7 MJ/Nm^3 (Sancho et al., 2008; Xiao et al., 2007). In addition, Lebanon struggles with poor waste management systems. Therefore, implementing co-gasification in future studies by blending plastic wastes with biomass can tackle different types of wastes alongside plastics while enhancing the product gas yields, as seen in the literature (Performances of syngas production, 2022; Ahmed et al., 2011).

4. Financial analysis

Lebanon's data were used for analysis to assess the significance of this process. First, it is crucial to see how much money it costs the Lebanese government to get rid of the plastic waste and compare it to how much it costs if the plastic is steam gasified. A rough economic analysis should be considered to evaluate the project's feasibility in the long run. In this section, the Net Present Value (NPV), Internal Rate of Return (IRR), Benefit to Cost Ratio (BCR), and Payback Period (PBP) are calculated and discussed after determining the OPEX and CAPEX.

4.1. CAPEX

Only the units in Fig. 1 are included in the CAPEX calculations for simplification. These units are a gasifier, pyrolizer, and two heat exchangers. The separator is not considered here because, as previously demonstrated, it is not recommended.

For a PE-only feed, the inlet flow rate to PYRO and GASIFIER is 797 kg/hr and 1251.3 kg/hr, which is around 0.00024 m^3/s and 0.03 m^3/s, respectively. For PE gasification at temperatures ranging between 590 and 800 °C, a pyrolizer residence time between 0.6 and 7.1 s is used (Sawaguchi et al., 1977). On the other hand, a gasifier requires a residence time between 0.86 and 3.23 (Brems et al., 2013) depending on the kinetics of the reaction (degree of conversion needed, reaction temperature, etc.). Therefore, to make the process continuous and without any delays avoiding the need for an extra reactor, a residence time of 4 s is chosen for both units.

With these numbers, a pyrolizer and a gasifier categorized as jacketed and agitated, having volumes of 0.001 and 0.122 m^3 are needed, respectively.

The units' type, volume, and material should be calculated to estimate the costs of the reactors, PYRO and GASIFIER (Matches' Reactor cost - autoclave, 2022). Because of its durability and high corrosion resistance, stainless steel was chosen as the material for these reactors.

For heat exchangers, the cost is determined by their type and corresponding power requirements (Matches' Fired Heater cost, 2022). From Aspen, HEATER1 and HEATER2 require 265 kW and 515 kW, respectively. The heaters are needed to increase temperatures to above 600 °C. As a result, a fired heater might be a good choice. In these heaters, fuel is burned, and the heat produced is used to heat the feed inside, which in this case is plastics.

4.2. OPEX

For the operating costs, plastic sorting, and transportation, the plant's total energy consumption, labor, and depreciation costs per year are considered.

In Lebanon, sorting is not done from the source, which means plastic waste will be included in the Municipal Solid Waste (MSW). According to the contract between the government and a private company that provides waste collection and treatment services, it costs the government 154.5 $/ton of MSW (Azzi).

As PE only, the input for the steam gasification process discussed before is 19.128 tons/day. Therefore, for the private company to collect such an amount of plastic, it needs to process around 138.709 tons of MSW/day, assuming that all plastic in the MSW is made up of PE. This will cost the government 9,224.16 $/day to handle 19.128 tons of plastic, as seen in Table 6.

The plant's costs have a total power consumption of 31,441.68 kWh, and the energy pricing in Lebanon is 0.096 $/kWh (Umeki et al., 2009) for industries. This means it will cost $3,018.4 in total to power the equipment. Another cost for the plant is collecting, transporting, and sorting 138.709 tons of MSW, which will cost 47.5 $/ton. So, treating the MSW to get the PE needed of 19.128 tons will cost 6,588.69 $/day.

The production flow rate, number of sections, and number of operators per section should be evaluated to calculate the labor costs. For a continuous plant that handles solids–fluids and produces 10 – 100 tons/day, 2 operators per section are needed. The plant produces around 24 tons a day and is divided into 2 sections: feed preparation and separation section and reactors section. As it is a continuous process, 168 h (7 days × 24 h) should be covered by operators in a week. A maximum of 40 h/week per operator is allowed, so around 4.2–5 shifts are required per section. Having around 5 shifts a day to cover the whole week, sick leaves, or holidays between the operators, 20 operators would be needed (Chemical Process Design and Simulation: Aspen Plus, 2022). For an average wage per operator of 40,000 $/year and managers getting 1.25 times what operators are getting, a total of 0.85 M$/year is required.

Finally, depreciation costs are calculated based on the time needed to depreciate the unit entirely (Net Present Value, 2022). Reactors and heat exchangers have an average depreciation time of 30 and 15 years, respectively. Dividing their CAPEX by these years, a total of 12780.2 $/year will have to be considered for depreciation for reactors and heat exchangers.

On the other hand, such a chemical process can result in 78,601.25 m^3 of syngas/day, which on average is priced around 0.18 $/$m^3$. Hence, it can be sold at a value of 14,148 $/day. At constant OPEX and revenue, >4.7 M$/year can be achieved. Detailed costs are seen in Table 7.

Table 6
Total Cost to Handle MSW in Lebanon.

Type	Value
Plastics (Tons/day)	19.13
MSW Plastic Composition (%)	13.79
MSW Needed (Tons/day)	138.71
Cost ($/Tons of MSW)	66.5
Total Cost ($/day)	**9224.16**

4.3. Feasibility study

The first estimate shows that the process is feasible at constant cash flows. However, an assumption is considered in the study to account for inflations and economic changes that could occur. A 10 % increase per year after the first year is assumed for OPEX, excluding depreciation, as it is a fixed value per year depending on the CAPEX, and a 5 % increase per year after the first year for labor costs. On the other hand, a corresponding increase of 15 % per year in revenue is assumed per year. Note that the CAPEX is multiplied by a factor of 3 to consider other units in the process or price changes.

A period of 5 years is used to analyze the economic feasibility of this study. The NPV is calculated based on eq. (3) which is helpful to compare to the initial investment at the current period. The IRR measures the return of an investment and is calculated using the excel function "IRR". The BCR identifies how much profit is made with respect to the initial CAPEX and is obtained using eq. (4). The PBP is the years needed to breakeven the initial investment made.

$$NPV = \frac{\text{Cash flow}}{(1+i)^p} \tag{3}$$

$$BCR = \frac{\sum_{p=0}^{p=5} NPV}{CAPEX} \tag{4}$$

Where Cash flow is the total inflow–outflow, i is the interest rate in Lebanon (~3.5 %), and p is the period number that ranges from 0 to 5 in years.

Now, comparing landfilling operations that would cost the Lebanese government 3.36 M$/year assuming no inflation, and steam gasification project by looking at Table 8, the total NPV is around 4 M$ after 5 years, which means the project can result in a present value at the end of the period, 6 times larger than the initial investment of about 0.6 (CAPEX × 3) M$. An IRR of 83 % illustrates that each 1 $ is returned as 1.83 $. A BCR of 6.5, which is >1, can be translated into a good project since the benefit made is 6.5 times the CAPEX, which can be returned in around 2 years. Not to mention that steam gasification can also positively impact reducing the CO_2 emissions from waste landfilling in Lebanon.

Table 7
CAPEX and OPEX.

Unit	Cost ($ or $/year)
CAPEX	
PYRO	500
GASIFIER	5600
HEATER1	69,014.64
HEATER2	119,637.9
Total CAPEX	**194,752.567**
OPEX	
Labor	0.85 M
Depreciation	12,780.17
Power	1.1 M
Sorting and Transportation	3.4 M
Total OPEX	**5.33 M**

Table 8
Feasibility Study Results.

Parameter	Value	Accepted Range
Total NPV	3.8 M$	>0 (Net Present Value, 2022)
IRR	83 %	>22 (Internal Rate of Return, 2022)
BCR	6.5	>1 (Benefit-Cost Ratio, 2022)
PBP	2 years	–

5. Conclusions

This study shed light on chemical recycling, where dry and steam reforming, air, steam, and co-gasification techniques were discussed in the literature. Steam gasification, however, was the focus of our model. The model was calibrated and implemented by gathering statistical data from different recycling firms in Lebanon to estimate the model's input. The model was simulated using Aspen Plus with initial conditions of 797 kg PE/hr and 500 kg PET/hr as input, steam to feed ratio of around 0.5, temperature of 700 °C, and pressure of 1 atm.

The effects of adding PET to PE, a flash separator to the gasifier product stream, gasifier temperature, pressure, and steam flowrate on the mole fractions were investigated using Aspen Plus. As a result, the optimum conditions are a temperature of 800 °C, a pressure of 1 atm, an S/F ratio of 0.57, and a water flow rate of 745 kg/hr. Also, adding a separator and inputting PET showed an insignificant increase in the mole fractions of the end product, so their elimination would be possible.

The financial study showed that the steam gasification project is more promising than landfilling. From the Lebanese government's perspective, instead of paying $3.36 M$/year to landfill and handling these wastes, they can be processed in a steam gasification plant. A rough feasibility study showed that at the end of 5 years, the total NPV is 6 times larger than the initial investment that can be returned within 2 years. This model helps save the environment by reducing waste that would otherwise be landfilled. It also would decrease CO_2 emissions when compared with other non-conventional processes. Based on a case study from Lebanon, this approach can be applied to any country by adapting the process inputs to the local circumstances.

On another note, future studies can focus on PET valorization since it did not benefit the product stream. For example, chemical recycling and utilization can be explored. Catalysis analysis and screening could be performed to determine the best catalysts for gasification. It is suggested to dig deeper into the feasibility study proposed by considering more factors for OPEX, like maintenance costs and fuel costs for fire heaters. A detailed process flow diagram, which could include what extra units must be considered for a complete operational flowsheet, is needed for the CAPEX. Finally, a kinetic study for the reactions can also be conducted to estimate proper residence times and corresponding reactor volumes.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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