Co-pyrolysis of oil palm empty fruit bunch and polypropylene: synergistic effects on blending ratios and product quality

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Abstract. The increasing accumulation of oil palm empty fruit bunches (EFB) and polypropylene (PP) waste necessitates sustainable management solutions. This study investigates the co-pyrolysis of EFB and PP in a fixed-bed reactor at temperatures ranging from 400 to 600 °C, utilizing blending ratios of 100:0, 75:25, 50:50, 25:75, and 0:100. The results revealed notable synergistic effects, particularly at a 75:25 EFB:PP ratio, which yielded 50.35% bio-oil, the highest gas yield (28.95%), and reduced biochar formation compared to pure EFB. The bio-oil composition showed increased aliphatic compounds and reduced oxygenated compounds, making intermediate ratios such as 75:25 ideal for balancing hydrocarbons and oxygenates. The char derived from co-pyrolysis maintained adequate porosity for applications such as adsorption, catalysis, and energy storage. Gaseous products such as CO_2, methane, and ethylene demonstrate a high energy potential, underlining the suitability of co-pyrolysis for industrial and energy applications. These findings confirm that co-pyrolysis is an efficient waste-to-resource strategy, optimizing bio-oil, char, and gas quality while addressing both biomass and plastic waste challenges.

1 Introduction

The increasing global demand for sustainable waste management and renewable energy sources has driven significant interest in thermochemical conversion technologies, such as pyrolysis, which can transform biomass and plastic waste into valuable products. Among biomass resources, oil palm empty fruit bunch (EFB), a lignocellulosic byproduct of the palm oil industry, represents a promising feedstock due to its abundance, renewability, and potential for energy recovery [1]. Similarly, polypropylene (PP), a significant contributor to global plastic waste accounting for approximately 20% of total plastic waste, necessitates

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innovative recycling strategies to mitigate its environmental impact [2]. Co-pyrolysis, the simultaneous thermal decomposition of biomass and plastic, has emerged as a viable solution to address these challenges. This process not only mitigates environmental issues associated with waste accumulation but also enhances the quality and yield of pyrolysis products, such as bio-oil, syngas, and biochar, through synergistic interactions. The integration of EFB and PP in co-pyrolysis leverages the hydrogen-rich nature of plastics to improve the hydrocarbon content of bio-oil, while the oxygen-rich biomass aids in stabilizing the pyrolysis process [3]. These synergistic effects make co-pyrolysis a compelling approach for producing high-value energy and chemical products, aligning with the principles of a circular economy.

Despite its potential, the influence of blending ratios on product quality and the underlying synergistic mechanisms during co-pyrolysis remain underexplored. Previous studies have extensively investigated the individual pyrolysis of EFB and PP, highlighting their potential for producing bio-oil, syngas, and biochar [4]. However, research on the co-pyrolysis of EFB and PP is limited, particularly in understanding how specific blending ratios affect product quality and yield. This gap is critical, as the interaction between EFB's oxygen-rich composition and PP's hydrogen-rich structure can significantly enhance pyrolysis outcomes, such as improving bio-oil stability and increasing hydrocarbon yields. Additionally, challenges persist in optimizing process conditions, such as temperature and heating rate, to maximize synergistic effects while minimizing undesirable byproducts. The novelty of this work lies in its comprehensive investigation of the co-pyrolysis of EFB and PP, with a focus on identifying optimal blending ratios that enhance product quality and process efficiency. By addressing these gaps, this study aims to provide new insights into the mechanisms underlying synergistic interactions during co-pyrolysis, offering a foundation for developing more efficient and sustainable waste-to-energy technologies. This research not only advances scientific understanding but also contributes to practical applications in renewable energy and waste management, supporting global efforts toward a circular economy.

Temperature and blending ratio are two factors that have a major influence on the co-pyrolysis technique. However, this condition may change according to the specific composition of the materials being treated. Thus, the synergistic effect of EFB and PP was observed using a fixed-bed pyrolysis reactor at temperatures varying from 400 to 600 °C and blending ratios of EFB:PP varying from 100:0, 75:25, 50:50, 25:75, and 0:100. This was done to determine the most appropriate operating temperature and blending ratio of EFB and PP for the co-pyrolysis technique. Gas chromatography combined with mass spectrometry (GC-MS) was used to analyze the bio-oil generated by the process and determine the composition of its chemicals. The remaining gas was evaluated using gas chromatography with a thermal conductivity detector (GC-TCD), and the biochar properties were examined using a Brunauer-Emmett-Teller (BET) instrument. This study is expected to demonstrate significant synergies between EFB and PP during co-pyrolysis, underlining the potential of this method to boost biofuel production while also providing a viable waste management option.

2 Materials and methodology

2.1 Materials

The primary materials for the co-pyrolysis process included empty fruit bunch powder from palm oil from Cikasungka Estate in Bogor, Indonesia, and polypropylene plastic pellets purchased from a vendor in Banten, Indonesia. Nitrogen gas is also required as a carrier gas in the process. Analytical-grade chemicals for GC-MS were also used in the analysis.

2.2 Feed preparation process

The feed for the co-pyrolysis process consisted of EFB and PP. The EFB was crushed, ground, and strained using 40 mesh strainer to obtain uniform EFB powder. The EFB were then dried overnight in a heated oven at 105 °C to eliminate moisture. The PP pellet was used directly without any pretreatment. EFB and PP were then blended at EFB-to-PP weight ratios of 100:0, 75:25, 50:50, 25:75, and 0:100. The total weight of the EFB and PP introduced into the pyrolysis reactor was 20 g.

2.3 Co-pyrolysis process

As illustrated in Fig. 1, co-pyrolysis of EFB and PP was performed in a fixed-bed batch reactor fitted with a heating jacket. The reactions were performed at temperatures ranging from 400 °C to 600 °C, atmospheric pressure, and a nitrogen gas flow rate of 50 mL/min for 40 min. The gas generated by the reactor was condensed in a condenser to produce the bio-oil. The bio-oil created during the procedure was characterized using gas chromatography-mass spectrometry (GC-MS) to identify its elemental composition, and the remaining gas was analyzed using GC-TCD. In addition, the biochar obtained from the process was analyzed using BET.

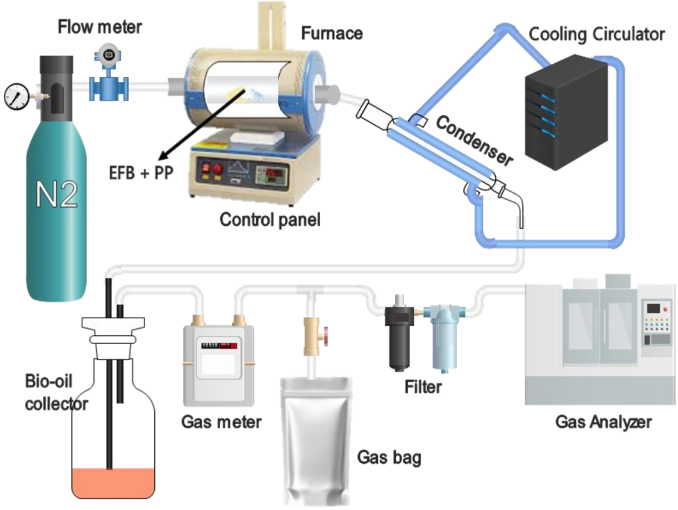

Fig. 1. Experimental setup for co-pyrolysis.

2.4 Evaluation of synergistic effects

The evaluation of synergistic effects can be done by comparing the yield of products; examples include bio-oil, biochar, and gas obtained from the experiment with the theoretical calculation results. The theoretical product yields of bio-oil were calculated from the weighted average results acquired from the individual pyrolysis of EFB and PP using Equation (1), where YEFB and YPP represent the yield, whereas WEFB and WPP represent the weight percentages of EFB and PP [5]. The assessment of the synergistic effect can be calculated using Equation (2), where ΔY indicates the disparities between the yield from experimental results and theoretical calculation results. A better synergistic effect was observed when ΔY was higher.

$$Y_{theoretical}=Y_{EFB}\ x\ W_{EFB}+Y_{PP}\ x\ W_{PP} \quad (1)$$

$$\Delta Y=Y_{experimental}-Y_{theoretical} \quad (2)$$

3 Result and discussion

3.1 The influence of operating temperature on product yield during the co-pyrolysis process

The co-pyrolysis of EFB and PP to yield bio-oil relies greatly on the operating thermal conditions. To obtain the optimum temperature for bio-oil production, co-pyrolysis was performed at temperatures ranging from 400 to 600 °C, and the yields of the outputs were compared, as shown in Fig. 2. The co-pyrolysis of EFB and PP with an equal blending ratio of 50:50 resulted in distinct product distributions at temperatures ranging from 400 to 600 °C. The bio-oil output yield at a temperature of 400 °C was 29.95 %, and this value dramatically increased to 64.5% when the temperature went up to 500 °C. Nevertheless, when the temperature was increased to 550 °C and 600 °C, the production of bio-oil decreased to 58.45 % and 55.1 %, respectively. The decrease in quantity can be ascribed to secondary decomposition reactions of volatile chemicals, wherein bio-oil undergoes further disintegration into gas at high temperatures [6].

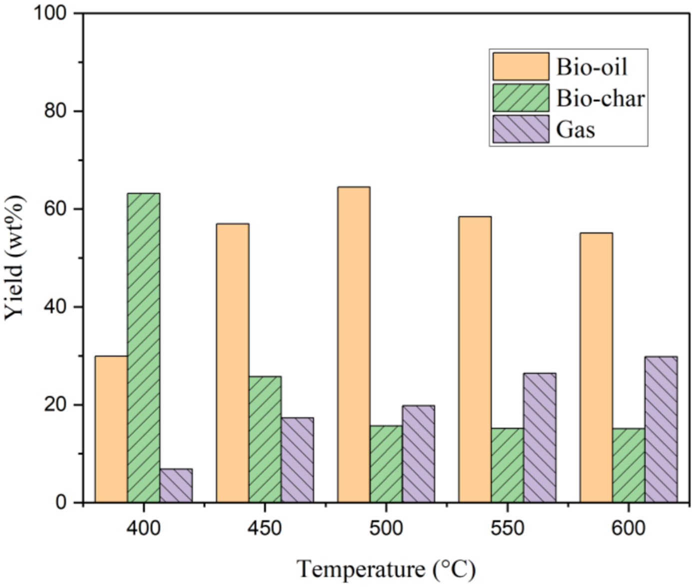

Fig. 2. The effect of temperature to the volume of product in co-pyrolysis of EFB:PP with ratio 50:50

The generation of biochar decreased significantly as the temperature increased. At a temperature reaching 400 °C, 63.2 quantity of the biochar was produced, which decreased dramatically to 15.7 % at 500 °C. It then remained reasonably constant at approximately 15.1 % at 550 °C and 600 °C. These findings indicated that the majority of the solid material underwent decomposition into volatile substances when exposed to elevated temperatures, resulting in a limited amount of solid residue. The biochar remained stable at temperatures above 500 °C, suggesting that most of the lignocellulosic components had already undergone decomposition by this stage.

Conversely, there was a substantial increase in gas generation with increasing temperature from 6.85 % at 400 °C to 29.8 % at 600 °C. This rise is a result of the heightened breakdown and fragmentation of volatile chemicals into gas at elevated [7]. In general, a temperature of 500 °C appears to be the most effective for achieving the highest possible bio-oil formation. However, temperatures above 500 °C tended to promote the creation of gas. This compromise offers valuable insights into optimizing the co-pyrolysis technique based on the intended product results.

3.2 The influence of EFB and PP blending ratio to the yield from the co-pyrolysis process

In this study, the co-pyrolysis of EFB and PP at 500 °C with varying blending ratios was performed, and the product yields were compared to obtain the optimum blending ratio in the co-pyrolysis technique. The results show a clear trend in the product yields, as shown in Fig. 3. The bio-oil yield increased as the proportion of PP in the blend increased. Starting from 42.85% for pure EFB, the yield increased to 50.35 % at EFB:PP ratio of 75:25, and reached 77.05 % at a ratio of 25:75. Pure PP produced the highest yield (89.5 %). PP significantly contributes to bio-oil production, as it decomposes into volatile components at higher rates than EFB. In contrast, biochar yield decreased as the proportion of PP increased. Pure EFB produced the highest biochar yield of 31.4 %, but this dropped significantly with more PP in the blend, reaching only 7.3 % for the 25:75 blend. Higher biochar content was produced because of the residual lignin present in the EFB, which requires a higher temperature for thermal degradation [8]. Pure PP yielded no biochar, reflecting its tendency to fully decompose into volatiles without leaving solid residues.

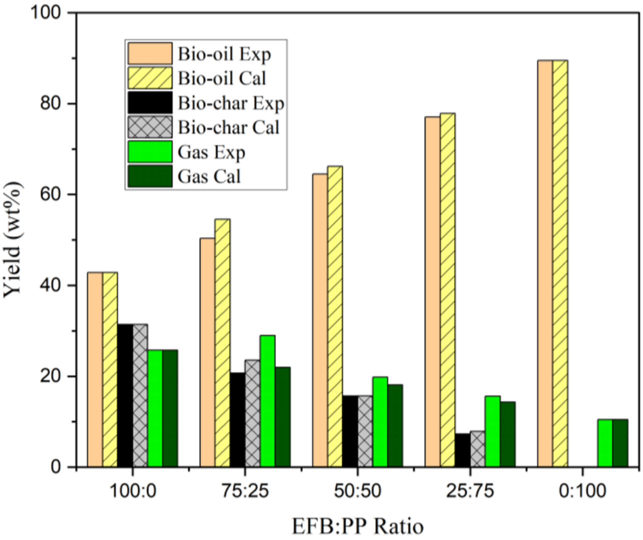

Fig. 3. The influence of EFB and PP blending proportion to the volume of product in co-pyrolysis temperature 500 °C from experimental results (exp) and theoretical calculation results (calc)

In this case, the gas production exhibits more variation. For pure EFB, the gas yield was 25.75 %, but the highest experimental yield was observed at an EFB:PP ratio of 75:25, producing 28.95 % gas, which was higher than the calculated value. As the PP content increased, gas production decreased, with pure PP yielding only 10.5 %. This indicates that the co-pyrolysis process favors liquid product formation as the proportion of PP increases. The main product expected from the co-pyrolysis of EFB and PP in this study was bio-oil. Therefore, based on Fig. 3, the optimum ratio was 75% EFB and 25% PP, which increased bio-oil production while decreasing the bio-char yield compared to pure EFB. In addition, this ratio produced the highest gas yield, which can also be a valuable product obtained from the co-pyrolysis technique.

The synergistic effect of EFB and PP can be analyzed by comparing the experimental and calculation results using Equation (1). As shown in Fig. 3, the bio-oil yield from the experimental results was slightly lower than the calculated results. This trend was also observed for biochar yield, except for the 50:50 ratio of EFB and PP. On the other hand, the experimental findings for the gas yield were higher than the calculation results. This tendency was attributed to the inhibition of the condensation and repolymerization reactions and the speeding up of the transformation of solids to gases caused by the formation of hydrogen-abundant radicals produced during the degradation of plastic [9].

For clarity, the distinction between the experimental and calculated yields (ΔY) was also calculated using Equation 2, and the results are shown in Table 1. It can be found that the ΔY for the creation of bio-oil and bio-char was negative which means that the synergistic effect did not support the creation of bio-oil and bio-char. Meanwhile, the ΔY for gas was positive, with the highest ΔY obtained for the EFB:PP ratio of 75:25. The blending ratio may have variable effects on the synergistic pathway. The results in Table 1 indicate a positive synergistic effect between EFB and PP in the production of gas. The assessment of synergistic effects between the materials used for the co-pyrolysis process can be very useful in directing the reaction towards the desired product, whether it is bio-oil, bio-char, or gas.

Table 1. Synergistic Effect Assessment.

EFB : PP Ratio	**Yield (%wt)**								
	Bio-oil			**Bio-char**			**Gas**		
	Exp	**Calc**	**ΔY**	**Exp**	**Calc**	**ΔY**	**Exp**	**Calc**	**ΔY**
75 : 25	50.35	54.51	-4.16	20.7	23.55	-2.85	28.95	21.94	7.01
50 : 50	64.5	66.17	-1.67	15.7	15.7	0	19.8	18.12	1.68
25 : 75	77.05	77.84	-0.79	7.3	7.85	-0.55	15.65	14.31	1.34

3.3 Product quality

3.3.1 Bio-oil composition

The composition of bio-oil produced from biomass, particularly from empty fruit bunches (EFB), reveals a complex interplay between various chemical compounds. At a 100:0 ratio of EFB, bio-oil is largely composed of oxygenated substances, including carbohydrates, phenols, and acids, which are reflective of the lignocellulosic nature of EFB. This is consistent with findings that highlight the significant presence of phenolic derivatives in bio-oils, which are known to contribute to their antioxidant properties and overall chemical behavior [10]. As the percentage of polypropylene (PP) increased in the feedstock increased, there was a notable decrease in these oxygenated substances, whereas aliphatics, which are characteristic of the thermal degradation of PP, became more prevalent, particularly at higher ratios of PP (25:75 and 0:100). Fig. 4 illustrates this transition in the chemical composition of the bio-oil, highlighting the shift from oxygen-containing substances to aliphatics as the PP content increases.

The phenolic components in bio-oil obtained from oil palm empty fruit bunches (EFB) exhibited a gradual decline as the EFB content decreased, indicating a reduced contribution from lignin-derived components. This observation aligns with the understanding that lignin, a significant component of EFB, is a primary source of phenolic substances in bio-oil. As the proportion of EFB in the feedstock diminishes, the availability of lignin decreases, leading to a corresponding reduction in the phenolic composition of the resulting bio-oil [11]. Aromatics derived from both EFB and PP showed relatively stable proportions across all ratios, suggesting synergistic pyrolytic pathways. The results, as presented in Fig. 4, demonstrate that co-pyrolysis at intermediate ratios (e.g., 50:50 or 75:25) yields a bio-oil composition with reduced oxygenated compounds and balanced hydrocarbon fractions, enhancing its potential as a fuel feedstock [12]. These findings underscore the ability of co-pyrolysis to valorize biomass and plastic waste while tailoring the bio-oil quality for energy applications through appropriate feedstock blending.

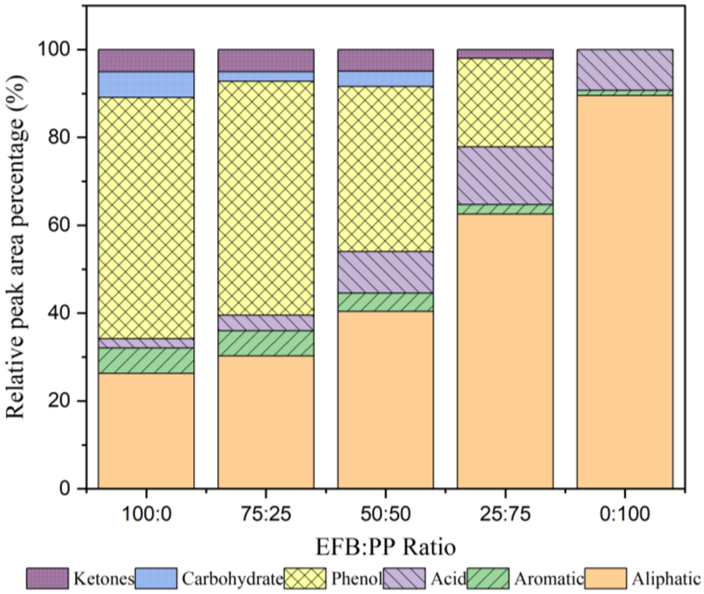

Fig. 4. Bio oil composition co-pyrolysis temperature 500 °C

3.3.2 Biochar characteristic

The surface areas and overall pore volumes of the chars derived from the pyrolysis of EFB and EFB:PP (50:50) are presented in Table 2. These findings indicate that the surface area of the 50 EFB:50 PP char (8.111 m²/g) was slightly lower than that of the 100 EFB char (8.900 m²/g). Similarly, the total pore volume followed the same trend, with the 50 EFB:50 PP char exhibiting a slightly decreased pore volume (0.04544 cc/g) compared to the 100 EFB char (0.04571 cc/g). The reduction in the surface area and pore volume observed for the 50:50 char can be attributed to the characteristic structural traits of lignocellulosic biomass and polypropylene. The porous cellular arrangement of EFB inherently facilitates the formation of larger surface areas and pore volumes during pyrolysis. In contrast, the degradation of polypropylene produces abundant hydrocarbons that adhere to the surface of char to form amorphous carbon, generating carbonaceous deposits that block pores and significantly reduce porosity [13]. Despite this reduction, the comparable pore volume and surface area values suggest that the co-pyrolysis of EFB and PP at a 50:50 ratio produces char with sufficient porosity. These findings highlight the role of material composition in tailoring char properties, which can be leveraged for specific applications, including adsorption, catalysis, fuel, and energy storage, where the surface area and pore size are critical parameters.

Table 2. Bio-char surface area.

EFB:PP ratio	Area of the surface (g/m^2)	Total porosity volume (cc/g)
50 : 50	8.111	0.04544
100 : 0	8.900	0.04571

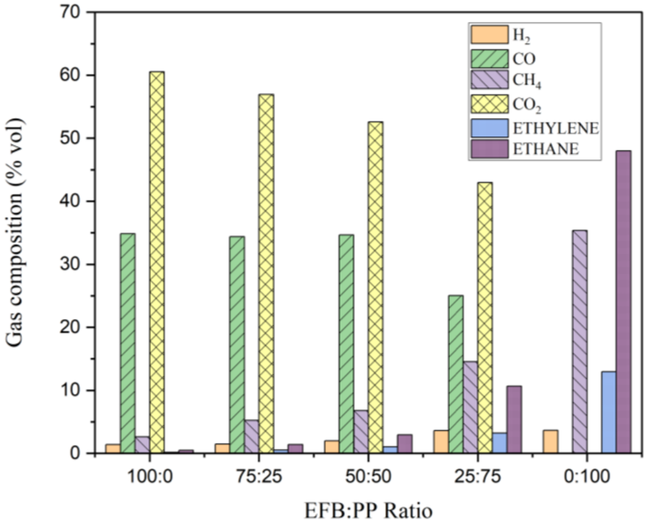

Fig. 5. Gas composition co-pyrolysis temperature 500 °C

3.3.3 Gas composition

The gas compositions from the pyrolysis of EFB and polypropylene at different blending ratios demonstrated distinct trends influenced by the feedstock composition. As shown in Fig. 5, carbon dioxide (CO2) is the most dominant gas produced across all blends, particularly in the 100 % EFB sample, where it reaches the highest concentration. This reflects the cellulose and hemicellulose structure of EFB, which undergoes significant decarboxylation reactions during pyrolysis [14]. In contrast, the CO2 concentration decreased as the proportion of polypropylene increased, indicating a reduced oxygenated functional group content in the feedstock. CO concentrations were lower overall but slightly higher in the 50:50 blend, indicating potential synergistic effects between EFB and polypropylene that enhance the cracking of oxygen-containing compounds. Methane (CH4) and ethylene showed a clear correlation with the polypropylene content, with the 100% polypropylene pyrolysis resulting in the highest production of these hydrocarbon gases. This occurs because the olefinic pyrolysis products generated by polypropylene undergo thermal cracking, producing additional light species [15]. The co-pyrolysis method allows for a customized gas composition, with polypropylene increasing hydrocarbon yields and EFB providing oxygenated gases, making it appropriate for a range of industrial and energy applications.

4 Conclusion

The co-pyrolysis of oil palm empty fruit bunch (EFB) and polypropylene (PP) at a 50:50 blending ratio is highly temperature-dependent, with 500 °C identified as the optimal condition, yielding 64.5 % bio-oil. This temperature maximizes bio-oil production and provides valuable insights for optimizing the co-pyrolysis processes. The blending ratio significantly influenced the product distribution, with a 75:25 EFB:PP ratio yielding 50.35 % bio-oil, the highest gas yield (28.95 %), and a reduced biochar yield compared to pure EFB, offering a favorable balance of product outcomes. The bio-oil composition varies with the blending ratio, with higher EFB ratios producing oxygenated compounds and increased PP content promoting aliphatics, making intermediate ratios, such as 50:50 or 75:25, ideal for balancing hydrocarbons and oxygenates. Co-pyrolysis not only optimizes bio-oil quality but also valorizes both biomass and waste plastics that are used in energy applications. Additionally, the co-pyrolysis of 100% EFB and EFB:PP (50:50) at 500 °C yielded chars with distinct chemical properties, where the 50:50 char retained sufficient porosity for applications in adsorption, catalysis, and energy storage. The gas composition shows that CO_2 dominates in 100 % EFB, whereas methane and ethylene concentrations increase with polypropylene content, making co-pyrolysis suitable for various industrial and energy applications by customizing the gas composition.

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