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Co-Gasification of Plastics and Biomass in a Downdraft Gasifier

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Abstract

The sharp rise in plastic consumerism and abundance of palm oil biomass waste, particularly the oil palm fronds, has brought about the challenges to treat waste sustainably. Co-gasification has the potential to become an effective technology for developing a long-term waste management system that reduces landfill emissions while optimizing energy recovery. However, there has been limited work on co-gasification of plastic with oil palm fronds, and this gap becomes a hindrance for the industry to take up the technology. This study aims to explore the potential of co-gasification as a sustainable waste management and energy recovery solution by examining the thermochemical behavior of plastic-biomass blends. Specifically, the objective is to investigate the impact of co-gasifying different plastics (high-density polyethylene, polypropylene, and polystyrene) with oil palm fronds (OPF). Experiments were performed in a downdraft gasifier with reaction temperatures between 750°C and 950°C as well as plastic proportions of between 0 wt.% and 30 wt.%. Increasing the plastic content in the feedstock blend led to a higher methane (CH_4) yield, while reducing the yield of other gases. Similarly, increasing the temperature to 950°C during co-gasification of polystyrene with OPF enhanced the production of synthetic gas (syngas) components such as hydrogen (H_2) and carbon monoxide (CO) while reducing the yield of CH_4. This is attributed to the increased cracking and reforming of volatile compounds at higher temperatures, converting them into permanent gases like H_2 and CO. Co-gasification with polypropylene resulted in the highest higher heating value (HHV_{gas}) as the temperature and plastic content rose. Syngas composition was influenced by both plastic type and blending ratio with OPF. Polystyrene had the greatest yield concentrations of H_2 and CO gases, while polypropylene showed the highest HHV_{gas} among other blends.

Categories: Renewable Energy Systems, Combustion and Alternative Fuels, Energy Efficiency and Conservation
Keywords: oil palm frond, polyethylene, polypropylene, polystyrene, co-gasification

Introduction

As the world transitions toward low-carbon, sustainable energy systems, the utilization of biomass, biofuels, and bioenergy provides viable pathways to meet growing energy demands and support the achievement of the United Nations Sustainable Development Goals (SDGs) [1]. Biomass, as a renewable energy source, plays a crucial role in mitigating climate change by reducing greenhouse gas emissions. However, a major challenge hindering technological advancement and commercialization is the efficient conversion and consistent availability of high-quality biomass for energy production [2]. The limited and variable supply of biomass feedstock further complicates the widespread adoption of biomass energy technologies. Competing demands from sectors such as agriculture, forestry, and industry exacerbate these supply constraints. Co-gasification of diverse biomass feedstocks has emerged as a promising solution [3], while combining biomass and plastic in gasification can effectively integrate the benefits of different feedstocks for efficient syngas production [4]. However, plastic waste gasification presents operational challenges due to agglomeration, highlighting the need for blending with biomass materials [5]. On the other hand, the increase in demand and production of plastics, due to the growth in population, has significantly contributed to the expansion of plastic waste globally. According to the Organization for Economic Co-operation and Development (OECD) (2022), global plastic production reached approximately 460 million tonnes in 2019, and it is projected to triple by 2060 if current trends continue [6]. The packaging sector remains the largest contributor, accounting for about 40% of total plastic use, followed by the construction (16%), automotive (8%), and textile (6%) industries [6]. These sectors not only drive production but also significantly influence the composition and volume of post-consumer plastic waste streams. Abundant it may be, there has been a greater sensitivity toward waste management and its disposal through landfills and incineration, such as the releasing of toxic gases. Recycling has always been a better alternative to waste disposal, as it lowers ecological footprint and saves the environment. However, according to a 2022 report from OECD [6], only 9% of the plastic produced has been recycled; 19% has been incinerated, and the remainder, 72%, ends up either in landfills or the environment.

Realizing the issue of waste disposal and the need for finding new alternative fuels, there have been many studies conducted to provide sustainable solutions for converting waste to cleaner energy [7,8].

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Gasification is an ideal solution in such cases, whereby diverse wastes undergo incomplete combustion to form syngas primarily composed of hydrogen (H_2) and carbon monoxide (CO) gases. Subsequently, this usable gas can be used to generate electricity as well as produce chemicals, liquid fuel, and other products. A gasification process that could blend both plastics and biomass would provide an innovative approach to chemical recycling. There are a noticeable number of studies investigating the characteristics of co-gasification, which offers several opportunities such as producing a low carbon footprint for the environment as well as a significant percentage of H_2 and CO in the syngas [9,10].

According to reports, oil palm fronds (OPF) are the most abundant, accounting for more than half of all oil palm biomass [11]. Due to its high energy content, Atnaw et al. [12] studied OPF gasification in a downdraft gasifier and proved its significant potential for clean energy. Blending various polymers with OPF for co-gasification would be advantageous because this strategy has the potency to minimize the environmental impact of agricultural and plastic waste disposal. Furthermore, co-gasification of biomass and plastics generates synergistic effects between the feedstock, yielding a considerably greater amount of energy from the syngas than that attained through gasification of single-type feedstock [13]. This research directly supports the attainment of SDGs 7, 9, 11, 12, and 13 by addressing clean energy generation, responsible waste utilization, and climate mitigation through innovative co-gasification technology. It is still unknown whether synergistic interactions exist in the thermal conversion of biomass and plastic [14]. The inclusion of plastic in gasification can partly assist in boosting the energy content of the syngas produced.

Several studies on co-gasification of various feedstock biomass were conducted quite recently [15]. They typically investigated a biomass and a single plastic [16,17], a biomass and coal [4], and various biomass materials [18-21]. Combining multiple plastics, however, remains under investigation. Basha et al. [16] co-gasified oil palm kernel shell (PKS) and polystyrene plastic using a downdraft gasifier. In addition, Saravanakumar et al. [22] conducted a pilot-scale study on solid wastes using a downdraft gasifier. Recently, Fazil et al. [5] compiled numerous studies on co-gasification of different feedstock using a fluidized bed gasifier. Nevertheless, due to reduced tar formation, lower cost, and simplicity of operation, downdraft gasifiers are indeed a more attractive choice for small power and heat applications. However, no research has been conducted on the air co-gasification of OPF and different plastics in a downdraft gasifier. There is also a scarcity of research on co-gasification with polystyrene, polypropylene, and polyethylene as co-feedstock. Thus, this work investigates the effectiveness of co-gasification with OPF biomass and three types of plastics, namely polyethylene (HDPE), polypropylene (PP), and polystyrene (PS), in a downdraft gasifier with different reaction factors. The biomass feedstock is chosen because of its high energy content, availability, and ease of access, and the plastic material is widely used in the household, as waste, and in the packaging industries. The aim of this study is to evaluate the co-gasification performance of OPF blended with HDPE, PP, and PS, with emphasis on syngas composition (particularly methane (CH_4) and H_2), energy content, and overall gasification efficiency. The remainder of this paper is organized as follows: the materials and methods used in the co-gasification experiments are presented, followed by a discussion of the results and analysis, and concluding with key findings and suggestions for future work.

Materials And Methods

Preparation of samples

Freshly pruned OPF, as depicted in Figure *1a*, were gathered from a corporate-owned plantation in Malaysia. Their leaflets were removed, and the petioles were chopped to small sizes suitable for drying under the sun, usually for three sunny days. To eliminate the moisture further, the petioles were oven-dried at 105°C for 24 hours, according to ASTM E1756-08, prior to being granulated. The granulated sample was then sieved using a 4-mm screen to crudely eliminate residues larger than 4 mm. Subsequently, a sample with a mean particle size between 2 mm and 3 mm was obtained using finer screens. This size range was selected for its optimal balance between gasification efficiency and ease of feedstock handling. Smaller feedstock sizes enhance reactivity by increasing the surface area available for gasification reactions, which is crucial for achieving high syngas yield. Additionally, this size range is commonly used in similar studies, as it promotes efficient heat transfer and minimizes the risk of blockages in downdraft gasifiers, which can occur with larger feedstock sizes [16]. Furthermore, previous research has shown that 2-3 mm feedstocks are optimal for ensuring uniform thermal decomposition and effective gasification of mixed feedstocks, including biomass and plastic waste [17]. The sample, as shown in Figure *1b*, was stored in a desiccator to maintain its dryness before it was oven-dried at 105± 2°C for 24 hours to reduce any remaining moisture content before the gasification process. This temperature is consistent with standard protocols for moisture removal in biomass and plastic feedstocks.

FIGURE 1: Oil palm frond biomass: (a) freshly pruned; (b) dried granulated

The three chosen types of plastics, i.e., HDPE, PP, and PS, were purchased in their virgin polymer forms from a commercial supplier. Their densities were 0.953 g/cm^3 (HDPE), 0.90 g/cm^3 (PP), and 1.04 g/cm^3 (PS). They, as shown in Figure *2*, were in the sizes of 2-4 mm. Also shown in Figure *2* are their respective resin identification codes used in the ASTM International Resin Identification Coding System. The smaller the identification code, the easier it is to recycle the plastic. These virgin polymers were typically in the form of granules, making them easier to prepare and feed into the gasifier.

HDPE, short for high-density polyethylene or polyethylene high-density (PEHD), represents a thermoplastic polymer derived from the ethylene monomer. Renowned for its remarkable strength-to-density ratio, HDPE finds extensive application in various sectors, including the manufacture of plastic bottles and corrosion-resistant piping.

Polypropylene (PP), alternatively referred to as polypropene, is a thermoplastic polymer synthesized through chain-growth polymerization using the monomer propylene. While sharing similarities with polyethylene, PP boasts a slightly higher hardness and enhanced heat resistance. Renowned for its fatigue resistance and notable chemical resilience, PP finds widespread utilization across various domains, including plastic packaging, fabrication of machinery and equipment components, and even in textile production.

PS is a synthetic polymer derived from monomers of the aromatic hydrocarbon styrene. Renowned for its versatility, PS finds extensive application in various fields, including protective packaging, container manufacturing, and bottle production. Classified as a thermoplastic polymer, PS remains solid at room temperature but exhibits flow properties when subjected to temperatures exceeding 100°C. Notably, PS is considered non-biodegradable, contributing to environmental concerns as it accumulates as litter, particularly in coastal areas and water bodies.

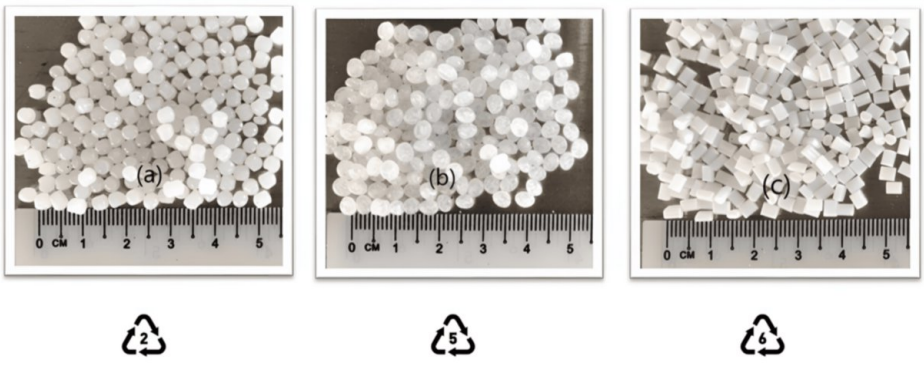

FIGURE 2: Plastics in granule form and their corresponding resin identification codes: (a) HDPE; (b) PP; (c) PS

HDPE, high-density polyethylene; PP, polypropylene; PS, polystyrene

Feedstock characterization

The ultimate and proximate analyses were conducted to characterize the OPFs and understand its composition and behavior during thermal conversion processes. The ultimate analysis determines the elemental composition of biomass, including carbon, hydrogen, nitrogen, sulfur, and oxygen content. This information is crucial for assessing the potential energy content and emissions associated with biomass utilization. The ultimate analysis was performed using a Perkin Elmer 2400 CHNS Analyzer according to ASTM D3176-09.

The proximate analysis, on the other hand, provides valuable insights into the physical and chemical properties of biomass, such as moisture content, volatile matter, fixed carbon, and ash content. These parameters influence the combustion behavior, thermal efficiency, and handling characteristics of biomass materials. In this study, proximate analysis of the samples was conducted using Perkin Elmer Pyris 1 TGA according to ASTM E1131-08.

Energy analyses were also conducted on all the four samples using IKA C-5000 Bomb Calorimeter, according to ASTM D5865-13 standard, to identify the relevancy of using these feedstock as a source of energy. The calorific values determined from the energy analyses represent the energy released upon complete combustion of a compound in the presence of oxygen. A high calorific value is preferable for fuels since it indicates the potential for releasing more energy when the fuel undergoes combustion.

Table *1* presents the characteristics of the feedstock in terms of calorific value, proximate analysis, and ultimate analysis. Regarding OPF, the biomass exhibits a carbon content of 42.6 wt.%, hydrogen content of 6.04 wt.%, and nitrogen content of 0.46 wt.%. The oxygen content, determined using the difference method, is 50.8 wt.%. These elemental values closely resemble those of other palm oil-based biomass [23]. In the proximate analysis, OPF comprises 1.2 wt.% ash, 80.8 wt.% volatile matter (VM), and 16.6 wt.% fixed carbon content (FCC). The calorific value of OPF is measured at 16.4 MJ/kg. On the other hand, plastics, being hydrocarbon polymers, exhibit high carbon contents: 85.2 wt.% (HDPE), 85.6 wt.% (PP), and 91.3 wt.% (PS). They also possess elevated hydrogen contents: 14.6 wt.% (HDPE), 14.4 wt.% (PP), and 8.67 wt.% (PS). In the proximate analysis, plastics show no ash content, 99.6 wt.% VM, and 0.04 wt.% fixed carbon. Due to their high carbon contents, plastics exhibit high calorific values: 46.3 MJ/kg (HDPE), 47.3 MJ/kg (PP), and 42.2 MJ/kg (PS).

Property	Biomass		Plastics		
	OPF		HDPE	PP	PS
Proximate analysis (wt.%)					
VM	80.8		99.2	99.3	99.6
FCC	16.6		0.8	0.66	0.4
Ash	1.2		-	-	-
Ultimate analysis (wt.%)					
Carbon	42.6		85.2	85.6	91.3
Hydrogen	6.04		14.6	14.4	8.67
Oxygen	50.8		-	-	-
Nitrogen	0.46		0.04	-	-
Sulphur	0.12		0.09	-	-
Calorific value (MJ/kg)	16.4		46.3	47.3	42.2

TABLE 1: Physical and chemical characteristics of OPF, HDPE, PP, and PS

OPF, oil palm fronds; HDPE, high-density polyethylene; PP, polypropylene; PS, polystyrene; VM, volatile matter; FCC, fixed carbon content

Experimental set-up

An externally-heated downdraft gasifier was employed for the co-gasification experiments. The complete setup is schematically illustrated in Figure *3*. The reactor, fabricated from SS316 stainless steel, had a cylindrical shape with an internal diameter of 67mm and a height of 750mm. It was designed for batch

operation and could accommodate up to 100g of feedstock. Threaded openings at the top and bottom enabled convenient loading, ash removal, and internal cleaning.

The feedstock was supported on a stainless steel grate positioned centrally and held by a rod connected to the bottom screw cap. Surrounding the reactor was a 1300 W, 240 V WATLOW ceramic-embedded radiant tube heater capable of achieving temperatures up to 1200°C. Temperature was regulated by a PID controller, with a Type-K thermocouple monitoring internal conditions. Heating was applied at a rate of 1°C per second, with the maximum operating temperature limited to 1000°C for safety considerations.

Air was introduced near the top of the reactor, while syngas was collected from the outlet at the base. Airflow during operation was maintained using a 2-hp air compressor and a rotameter. The resulting product gas first passed through condensation bottles immersed in an ice bath to remove moisture, followed by impingers containing organic solvents to trap tar. A gas conditioning unit further purified the gas by eliminating particulates and residual moisture.

The composition of the product gas specifically CO, CO_2, CH_4, and H_2 was continuously analyzed using an Emerson-Rosemount X-Stream X2GP online gas analyzer. The entire system, including thermal control and gas monitoring, was interfaced with a computer for real-time data acquisition and control.

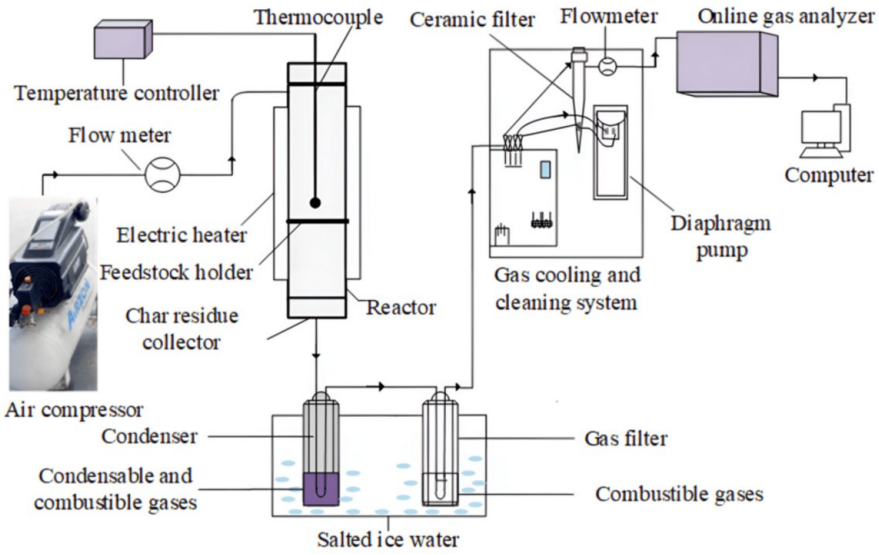

FIGURE 3: Experimental setup for the co-gasification of HDPE, PP, and PS plastics with OPF

OPF, oil palm fronds; HDPE, high-density polyethylene; PP, polypropylene; PS, polystyrene

Experimental procedure

The operation was carried out by heating the reactor to a predetermined reaction temperature and conditions as summarized in Table *2*. The air supplied by the compressor was maintained at a constant rate of 2.5 L/min. Throughout the experiment, the mass of mixed feedstock was kept constant at 50g and manually fed into the reactor from the top. Prior to feeding, both the OPF and plastic materials were ground and sieved to the required sizes (2-3 mm for OPF and 2-4 mm for plastics). The weighed portions were then manually blended in a clean stainless-steel container using a hand-held spatula to ensure homogeneous mixing and minimize variability during gasification. An online gas analyzer was used to determine the cumulative average volume percentages of H_2, CO, CO_2, and CH_4 in the product gas.

Parameters	Values			
Temperature (°C)	750	850	950	
Air flow (L/min)	2.5			
Blending ratio (wt.%)	0	10	20	30
Size of biomass (mm)	2-3			
Size of plastics (mm)	2-4			

TABLE 2: Experimental factors and fixed parameters for downdraft gasification of plastics and OPF

OPF, oil palm fronds

Results

In this work, co-gasification experiments were performed at reaction temperatures ranging between 750°C and 950°C and an air flow rate of 2.5 L/min. The resulting synthetic gas was analyzed in terms of the effects of gasification temperature and plastic contents.

Effects of temperature on synthetic gas composition

In the study on the effect of temperature, the plastic content was limited to 10% only due to the limitation of resources, and furthermore, the study is aimed at understanding the basic trend. The reaction temperature is found to be one of the most important factors influencing the gasification performance of polymers mixed with OPF. Figure *4* shows the variation of gas compositions (CO, CO_2, CH_4, and H_2) of the syngas for different gasification temperatures for the 10:90 plastic-OPF mixtures for HDPE, PP, and PS. The temperature is shown to have a significant impact on the gas compositions. The concentrations of all the combustible gases (CO, H_2, and CH_4) are shown to increase with temperature. Nonetheless, the CO_2 concentration shows the opposite trend, and this may be good in view of the need to reduce the overall emission of the gas, which is one of the main contributors to global warming.

CO rises with temperature for every blend; PS and OPF had the greatest CO concentrations as the concentration rose from 14.6% to 20.5%. The CO content of HDPE and OPF increased from 10.3% to 13.5% when the gasification temperature was increased from 750°C to 950°C. The blend of PP and OPF, on the other hand, shows an increase in CO concentration from 11.5% to 16.8%. All blends had the maximum CO_2 gas composition at 750°C. However, as the temperature rose, the volume content of CO_2 in all combinations decreased. The CO_2 concentration of PS:OPF and PP:OPF blends decreased from 19.7% to 12.9% and 16.2% to 13.7% at 950°C, respectively. A similar pattern can be seen for the HDPE-OPF blend, which fell from 13.7% to 11.5%.

It is also shown in Figure *4* that the concentration of H_2 gas increases with temperature. For the mixture of HDPE-OPF, the concentration of H_2 increased from 3.9% to 12.1% as the temperature increased. Likewise, the blend of PP-OPF showed a rise of H_2 concentration from 7.5% to 11.6%. At 950°C, PS-OPF showed the highest concentration of H_2 among other blends at 14.7%. This result is consistent with other studies where maximum H_2 concentration was achieved for PS blended with biomass [24,25]. It was discovered that at 950°C, the highest production of H_2 can be seen for all mixture fractions of 10 wt.% plastics in OPF using HDPE, PP, and PS. Therefore, 950°C is discovered to be an ideal temperature where maximum H_2 concentration is generated. The water-gas reaction can explain the rise in H_2 concentration with temperature. The water-gas interaction also contributes to the increase in CO with temperature.

The content of CH_4 increased as the temperature was raised from 750°C to 850°C. But the CH_4 content decreased as the temperature rose further to 950°C. As shown in Figure *4*, similar trends were shown for all blends. At 950°C, PS: OPF showed the lowest CH_4 concentration among other blends at 12.2%, with HDPE: OPF at 12.2% and PP: OPF at 19.9%.

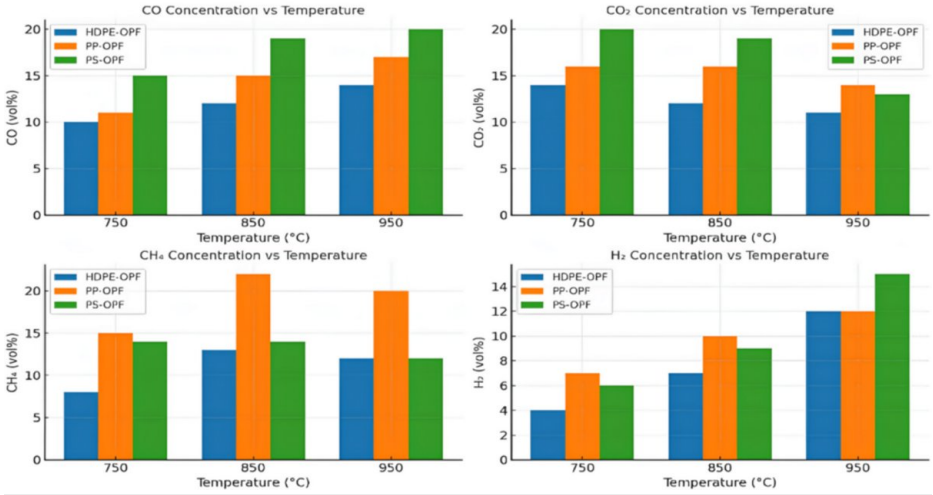

FIGURE 4: Gas composition vs temperature for HDPE, PP, and PS co-gasified with OPF

OPF, oil palm fronds; HDPE, high-density polyethylene; PP, polypropylene; PS, polystyrene

Effects of temperature on the higher heating value of syngas

The main performance parameters for the co-gasification, which were the gas composition and the higher heating value (HHV), could be analyzed for energy efficiency. Furthermore, the HHVgas was influenced by the composition of the product gas. Shown in Figure *5* is the variation of HHV of the resulting syngas as a result of co-gasification for different gasification temperatures and the types of plastics at a mixing ratio of 10% plastic and 90% biomass. As illustrated in Figure *5*, the HHVgas of the resulting syngas increases with temperature. Higher temperatures produce additional gas components such as H_2, CO, and CH_4, impacting the HHVgas of HDPE: OPF ranging from 5.2 MJ/Nm^3 to 8.1 MJ/Nm^3 and PS: OPF ranging from 8.1 MJ/Nm^3 to 9.3 MJ/Nm^3. PP: OPF has the highest HHVgas, with values ranging from 8.4 MJ/Nm^3 to 11.5 MJ/Nm^3.

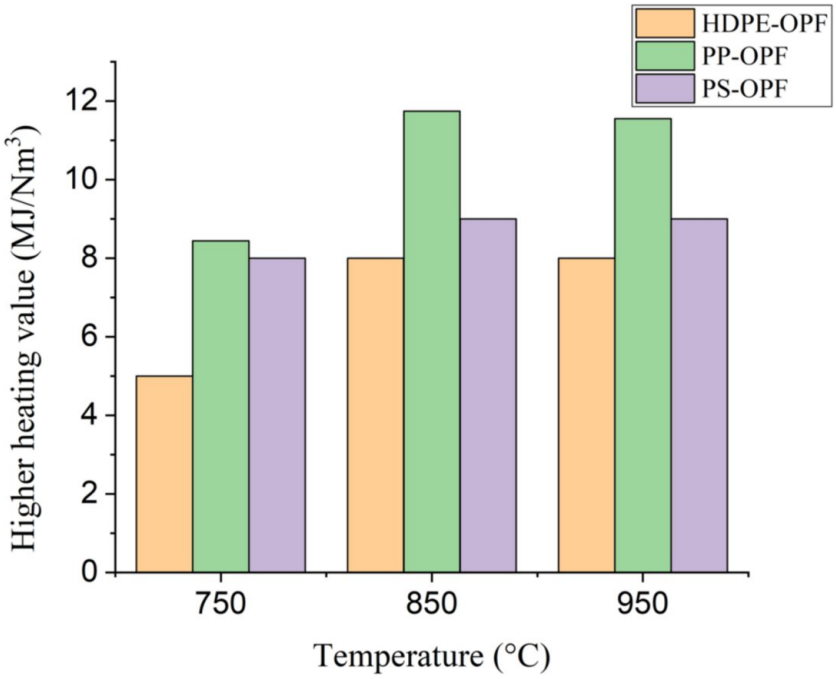

FIGURE 5: Effect of the gasification temperature on the syngas HHVgas of 10 wt.% plastic to 90 wt.% OPF mixture

OPF, oil palm fronds; HDPE, high-density polyethylene; PP, polypropylene; PS, polystyrene; HHV, higher heating value

Effects of plastics content on syngas composition

The influence of plastic content on gas composition was investigated at a gasification temperature of 850°C and a constant air flow rate of 2.5 L/min. The plastic content in the biomass feedstock varied between 0 and 30 wt.%. Figure *6* presents the variations in syngas composition for different plastic blends. When 100% OPF was gasified, the resulting syngas contained 15.4% CO, 16.8% CO_2, 8.1% H_2, and 8.6% CH_4. The results indicate that gas composition is strongly influenced by both the plastic type and blending ratio. For CO, HDPE blends showed a decreasing trend: 14.5% at 10%, 13.6% at 20%, and 12.8% at 30%, suggesting that higher HDPE ratios may suppress incomplete combustion. PP followed a similar trend, while PS exhibited a peak CO concentration of 15.7% at 10% before dropping to 13.2% and 12.0% at 20% and 30%, respectively, likely due to its aromatic structure enhancing CO formation at low concentrations. CO_2 concentrations declined with increasing HDPE and PP content. For HDPE, values were 15.2% at 10%, 14.0% at 20%, and 12.9% at 30%. In contrast, PS led to a slight rise in CO_2 at 10% (17.4%) before decreasing at higher blends, indicating varying oxidation pathways. CH_4 concentrations increased consistently with plastic content. In HDPE blends, CH_4 rose from 10.2% at 10% to 12.0% and 13.6% at 20% and 30%, respectively. A similar trend was observed for PP and PS, where PS exhibited the highest CH_4 at 30% (14.8%), highlighting intensified thermal cracking and hydrocarbon release with higher plastic loading. Hydrogen (H_2) production peaked at 10% blending for HDPE and PP, reaching 10.6% and 10.3%, respectively, before declining to 9.2% and 8.9% at 30%. For PS, H_2 decreased steadily with blending, from 7.9% at 10% to 6.8% at 30%, implying that excessive plastic addition may hinder reforming reactions or reduce biomass-derived hydrogen generation. Overall, the data suggest that moderate plastic blending, especially at 10%, enhances syngas quality, with each plastic type affecting gas yields differently due to variations in chemical structure and decomposition behavior. The increasing CH_4 trend aligns with findings from a related study [26] involving biomass waste, plastic waste, and coal, reinforcing the synergistic effect of plastic content on thermal cracking and hydrocarbon formation.

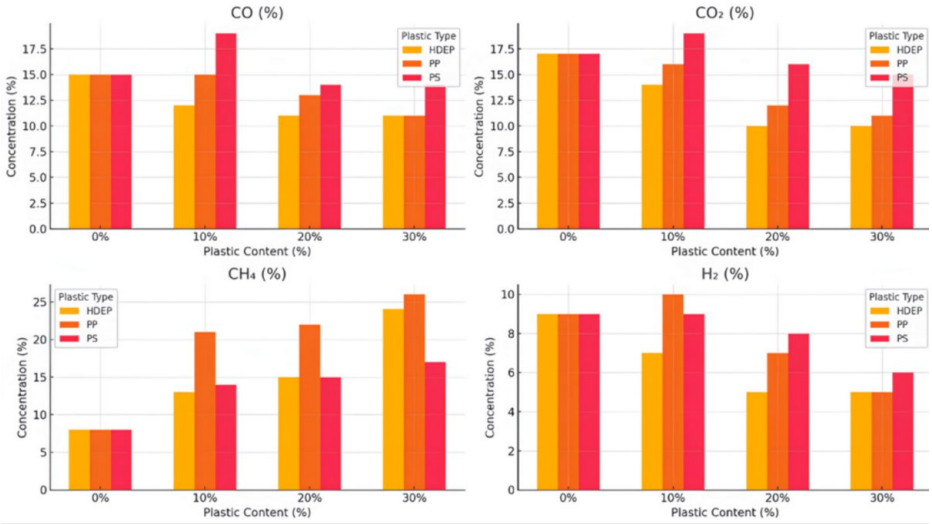

FIGURE 6: Variations of gas composition for different plastic content at 850°C

Effects of plastics content on heating value of syngas

The proportion of plastic in the OPF mixture also has a remarkable effect on the higher heating value (HHVgas) of the resulting syngas. Shown in Figure 7 is the variation of the HHVgas of the syngas for various plastics at different contents (in weight percentage, wt.%) at a gasification temperature of 850°C. As depicted in the figure, the HHVgas of the gas generally increases as the plastic content in the feedstock increases, with the PP-OPF blend having the highest HHVgas content. When the HDPE percentage in the feedstock was increased from 0 to 30%, the HHVgas increased from 6.30 to 11.6 MJ/Nm^3. Similarly, for PS and OPF, HHVgas increased from 6.30 to 9.30 MJ/Nm^3.

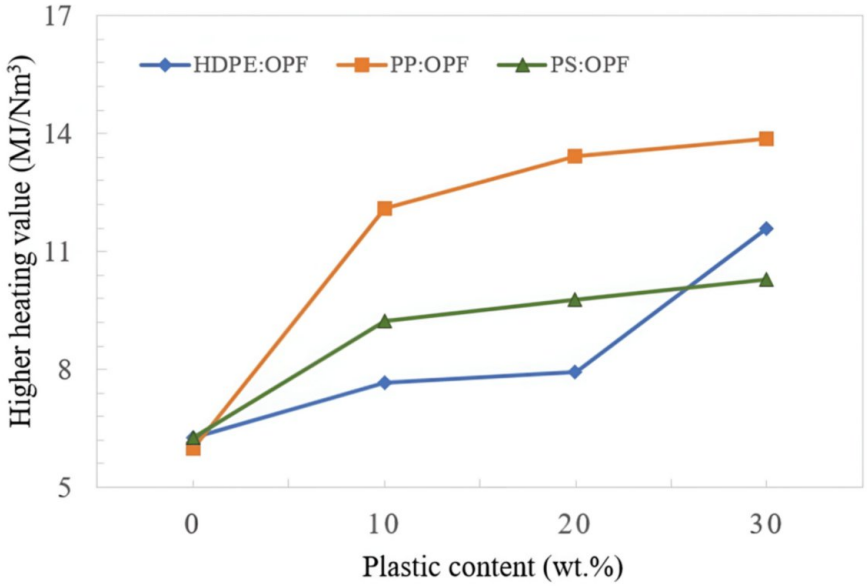

FIGURE 7: HHVgas of different plastic content to OPF mixture at 850°C

HHV, higher heating value; OPF, oil palm fronds

Discussion

Effects of temperature on syngas composition

The effect of gasification temperature on syngas composition revealed that increasing the temperature from 750°C to 950°C significantly enhanced the production of combustible gases. The CO concentration

increased from 10.3% to 13.5% for HDPE-OPF, 11.5% to 16.8% for PP-OPF, and 14.6% to 20.5% for PS-OPF. In contrast, CO_2 concentration decreased, suggesting the dominance of the Boudouard reaction ($C + CO_2 \boxtimes 2CO$) at higher temperatures (>850°C), which promotes CO formation and reduces CO_2 emissions [16]. The concentration of H_2 also increased with temperature, ranging from 3.9% to 12.1% for HDPE-OPF, 7.5% to 11.6% for PP-OPF, and peaking at 14.7% for PS-OPF at 950°C. The decline in CH_4 concentration at elevated temperatures is likely due to thermal cracking into CO and H_2 [27]. Among all blends, PS-OPF generated the most favorable syngas quality in terms of H_2 and CO yield. Notably, all plastic-OPF blends exhibited their maximum CO_2 concentration at 750°C. This is primarily due to the dominance of oxidation reactions (e.g., $C + O_2 \rightarrow CO_2$) at lower temperatures, which promote the direct formation of CO_2 over other gasification products. At this stage, reduction reactions, especially the Boudouard reaction ($CO_2 + C \rightarrow 2CO$), are thermodynamically less favorable and kinetically limited, thereby reducing the conversion of CO_2 to CO [28]. Furthermore, thermal cracking and reforming of long-chain hydrocarbons from plastics is less efficient at 750°C, limiting the generation of secondary syngas products like CO and H_2 [29,30]. As a result, CO_2 levels remain high, while combustible gases are suppressed at lower gasification temperatures.

Effects of temperature on the higher heating value (HHV) of syngas

As the gasification temperature increased, the production of combustible gases-H_2, CO, and CH_4-also rose, leading to a notable increase in the syngas higher heating value (HHV_{9as}). For the HDPE-OPF blend, HHV_{9as} increased from 5.2 MJ/Nm³ to 8.1 MJ/Nm³, while PS-OPF ranged from 8.1 MJ/Nm³ to 9.3 MJ/Nm³. The PP-OPF blend exhibited the highest HHV_{9as}, rising from 8.4 MJ/Nm³ to 11.5 MJ/Nm³. This improvement is largely attributed to PP's higher CH_4 yield, which significantly enhances the energy content of the syngas [16]. Although 950°C yielded the best syngas composition and HHV across all plastic-OPF blends, such elevated temperatures also entail increased energy consumption and operational costs. From a process optimization standpoint, there is a clear tradeoff between syngas quality and energy efficiency. Higher temperatures favor endothermic reactions and thermal cracking that improve H_2 and CO generation, but they also require greater fuel or electricity input, which may impact the overall economic viability. Therefore, selecting an appropriate temperature should strike a balance between syngas quality and thermal energy demand, depending on the intended application and scale of operation.

Effects of plastic content on syngas composition

At a constant gasification temperature of 850°C, increasing plastic content from 0 to 30 wt.% in the feedstock led to a consistent increase in CH_4 concentration. Among the plastics studied, PP yielded the highest CH_4 concentration (25.7%), followed by HDPE (24.0%) and PS (16.7%). Conversely, the concentrations of CO, CO_2, and H_2 declined with higher plastic content. This trend aligns with other findings in biomass-plastic and biomass-coal co-gasification studies, where plastics contribute more hydrocarbon volatiles, favoring CH_4 over H_2 formation [26].

Effects of plastic content on heating value of syngas

An increase in plastic content significantly enhanced the HHVgas. For instance, increasing HDPE from 0% to 30% in the feedstock raised HHVgas from 6.3 MJ/Nm³ to 11.6 MJ/Nm³, while PS-OPF increased from 6.3 MJ/Nm³ to 9.3 MJ/Nm³. The PP-OPF mixture again achieved the highest energy value, with HHVgas rising from 6.3 MJ/Nm³ to 12.2 MJ/Nm³ at 30 wt.% PP. This increase is directly linked to the higher CH_4 concentration, which has a greater calorific value compared to CO or H_2. These findings are consistent with previous research on co-gasification of PKS and plastics [16].

CH_4 vs H_2 trends and syngas optimization goals

The results clearly demonstrate a trade-off between CH_4 and H_2 production in the co-gasification process. Higher plastic content increases CH_4 due to plastics' high volatile matter and hydrocarbon content, which enhances CH_4 formation during devolatilization. However, H_2 formation relies on high-temperature gas-solid reactions like steam reforming and the water-gas shift reaction, which are more pronounced at elevated temperatures but less sensitive to plastic proportion.

In the context of sustainable energy systems, the long-term objective of this study is to maximize H_2 production, given its relevance to clean fuel applications, low-emission combustion, and hydrogen economy development. However, CH_4-rich syngas is also advantageous for improving heating value, making it suitable for combustion and thermal energy generation. Therefore, this study provides insights into optimizing gasification parameters to favor either H_2 or CH_4 production depending on the targeted application. Specifically, 950°C is identified as the ideal temperature for H_2 enrichment, while 30 wt.% plastic content offers the best yield for CH_4-rich, high-HHV syngas.

This study presents significant improvements over previous co-gasification works in several ways: unlike many studies focusing on single plastics, this work systematically investigated three plastics (HDPE, PP, and PS) blended with OPF under uniform conditions. Compared to Fazil et al. [5], who reported lower H_2 (around 10%) for similar systems, our PS-OPF blend achieved 14.7% H_2 at 950°C, showing superior hydrogen yield. PP-OPF achieved HHV of 12.2 MJ/Nm³, higher than typical biomass-only gasification

(often <9 MJ/Nm³) and surpassing HHV values reported in studies [16,22] for similar feedstocks. Operational advantages: downdraft gasifier performance under our conditions showed low tar, steady gas output, and improved gas quality. Environmental benefit: our results offer a scalable solution for agro-waste and plastic waste co-processing, supporting SDGs 7, 9, 11, 12, and 13 more directly than prior works.

Conclusions

This study investigated the co-gasification of OPF with three types of plastic, HDPE, PP, and PS, using a downdraft gasifier under varying temperatures (750-950°C) and a constant air flow rate of 2.5 L/min. The effects of temperature and plastic content on syngas composition and energy performance were systematically analyzed. The results revealed that increasing the gasification temperature led to higher concentrations of combustible gases (CO, H_2, CH_4), while CO_2 levels decreased, indicating improved carbon conversion and potential emission reductions. Among the plastics tested, PS-OPF blends yielded the highest H_2 concentration (14.7%) at 950°C, while PP-OPF blends achieved the highest HHV of 12.2 MJ/Nm³ due to elevated CH_4 content. Plastic content also significantly influenced syngas quality. Increasing the plastic proportion up to 30 wt.% improved the HHV, but beyond this level, gas quality declined due to reduced char reactivity and limited gasification reactions. Based on the findings, the optimum co-gasification parameters for maximizing both H_2 production and syngas calorific value are as follows: temperature: ~950°C, plastic content: 10-20 wt.% (balanced H_2 and CH_4 production), air flow rate: 2.5 L/min, particle size: 2-3 mm, best performing blends: PS-OPF for highest H_2 output, and PP-OPF for maximum HHV. These conditions enabled the generation of clean, energy-rich syngas with a favorable H_2-CH_4 balance, reduced CO_2 emissions, and strong potential for flexible applications in heat, power, and hydrogen energy systems. The study thus offers a promising waste-to-energy pathway supporting clean energy goals and circular economy principles. However, some limitations were observed. Higher plastic content beyond 30 wt.% led to a decline in gas quality, likely due to reduced char reactivity and increased tar formation, which may impact overall system efficiency. Despite this, the co-gasification approach provides several benefits, including reduced plastic and biomass waste, improved syngas quality, and potential for application in decentralized energy systems. Future work should focus on pilot-scale trials, tar mitigation strategies, and comprehensive techno-economic and environmental assessments to evaluate the long-term viability of plastic-biomass co-gasification.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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