

Modeling Syngas Generation from Co-Gasification of Refuse-Derived Fuel and Tire Waste in Fixed Bed Gasifier

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The objective of this research was to investigate the effects of operating parameters on syngas quality and process performance metrics during the co-gasification of refuse-derived fuel (RDF) and tire waste (TW). This was modeled using simulations by Aspen Plus v10. The influence of gasification temperature, steam flow rate, and air flow rate on syngas composition, lower heating value (LHV), cold gas efficiency (CGE), and syngas yield were thoroughly evaluated. Simulation results revealed an optimal temperature of 700 °C, combined with 0.5 kg/h steam and 0.5 kg/h air flow rates, maximizing the LHV at 17.62 MJ/kg (approximately 14.5 MJ/Nm³), CGE at 75.38 %, and the weight of syngas at 1.28 kg/kg. The optimized conditions facilitated a balanced formation of combustible gases while minimizing carbon losses, generating a high-quality syngas with desirable properties from the co-gasification of RDF and TW.

1. Introduction

Municipal Solid Waste (MSW) management faces challenges including increasing volume, environmental impact of landfills, and failure to recover resources (Srivastava et al., 2015). Refuse-Derived Fuel (RDF) and tire waste (TW) are two major components of MSW contributing to these issues. While recycling, composting, and anaerobic digestion offer partial solutions, thermal techniques like gasification present significant potential for volume reduction, energy recovery, and pathogen/toxin destruction.

Previous research has explored gasification of RDF and TW separately, with limited studies on their co-gasification. Le Tan et al. (2022) investigated RDF gasification, focusing on syngas composition and energy recovery, but didn't address RDF composition heterogeneity, which significantly impacts gasification performance. Haydary et al. (2023) examined RDF as a feedstock but didn't consider its combination with other waste streams to enhance gasification efficiency. Rogachuk and Okolie (2023) studied tire waste gasification, highlighting its high calorific value and potential as a fuel source, but didn't explore synergistic effects of combining tire waste with other feedstocks.

Co-gasification of RDF and TW in a fixed bed gasifier offers potential advantages, including balanced syngas composition and higher calorific value. However, the literature lacks comprehensive studies on optimal operating conditions for this feedstock combination. Fernandez-Lopez et al. (2017) demonstrated Aspen Plus's utility for gasification process simulation but didn't extend to the complex interactions in RDF and TW co-gasification.

Significant research gaps exist, including limited understanding of RDF-TW synergistic effects during co-gasification, lack of optimization studies for these feedstocks in fixed bed gasifiers, insufficient exploration of feedstock variability impact on gasification performance and syngas quality, and absence of comprehensive techno-economic and environmental assessments for RDF and TW co-gasification systems.

This research aims to fill these gaps by modeling and simulating RDF and TW co-gasification in a fixed bed gasifier using Aspen Plus. Primary objectives include optimizing syngas quality by evaluating critical parameters like gasification temperature and equivalence ratio, enhancing process efficiency through maximizing syngas yield, lower heating value, and cold gas efficiency, and identifying the optimal operating regime balancing syngas quality and overall process efficiency.

The study's novelty includes developing a comprehensive Aspen Plus model for RDF and TW co-gasification, accounting for complex feedstock interactions, identifying optimal operating conditions, analyzing synergistic

effects between RDF and TW, providing insights into feedstock blending strategies, and assessing feedstock variability impact on gasification performance.

By addressing these research gaps and providing novel insights into RDF and TW co-gasification, this study will contribute to developing more efficient and sustainable waste management strategies, supporting the transition towards a circular economy in the waste sector.

2. Materials and methods

2.1 Materials

The proximate and elemental compositions, as well as the higher heating values (HHV) of the RDF and TW used in the modeling are reported in Table 1. RDF and TW were mixed for co-gasification at a mass ratio of 1:1 and a total material flow rate of 2 kg/h. The HHV of the RDF and TW mixture was calculated as 24.75 MJ/kg. The average hydrogen content (H) was 6.31 %, and the average moisture content was 2.52 %. Lower heating value (LHV) of material was calculated by Eq(1).

$$LHV = HHV (1 - M) - 2.44M \quad (1)$$

where M is the moisture content. The LHV of the mixture was estimated to be approximately 23.31 MJ/kg. For the simulation, the following components were defined: conventional gasification gases: O₂, N₂, CO, CO₂, CH₄, H₂O, and H₂. Other relevant components: C, S, ASH, C₆H₆, C₇H₈, C₈H₈, C₁₀H₈, C₉H₈, C₆H₆O, C₈H₁₀, H₂S, and SO₂. These components were included to accurately represent the complex composition of the feedstocks and the gasification products in the simulation model.

Table 1: Proximate and elemental composition and HHV of RDF (Haydary et al., 2023) and TW (TNO, 2022)

Material	Moisture (wt%)	Volatile matter (wt%)	Fixed carbon (wt%)	Ash (wt%)	HHV (MJ/kg)
TW	0.81	63.65	26.28	9.27	34.62
RDF	4.24	70.29	0.45	25.02	14.88
RDF and TW	2.52	66.97	13.37	17.15	24.75
Material	C (%)	H (%)	N (%)	S (%)	O (%)
TW	75.36	7.09	0.95	1.76	5.42
RDF	38.02	5.52	0.77	0.34	26.09
RDF and TW	56.69	6.31	0.86	1.05	15.76

2.2 Simulation description

The co-gasification of RDF and TW was simulated using Aspen Plus process simulation software (Aspen plus V10, 2017). The simulation model consisted of several unit operation blocks, including DRYING, PYROLYSI, MOIS-SEP, ASH-SEP, GASIFIER, COMBUST, and TAR-SEP (Figure 1), each employing different modules such as RStoic, RYield, SSplit, and FSplit to represent the respective processes (Table 2).

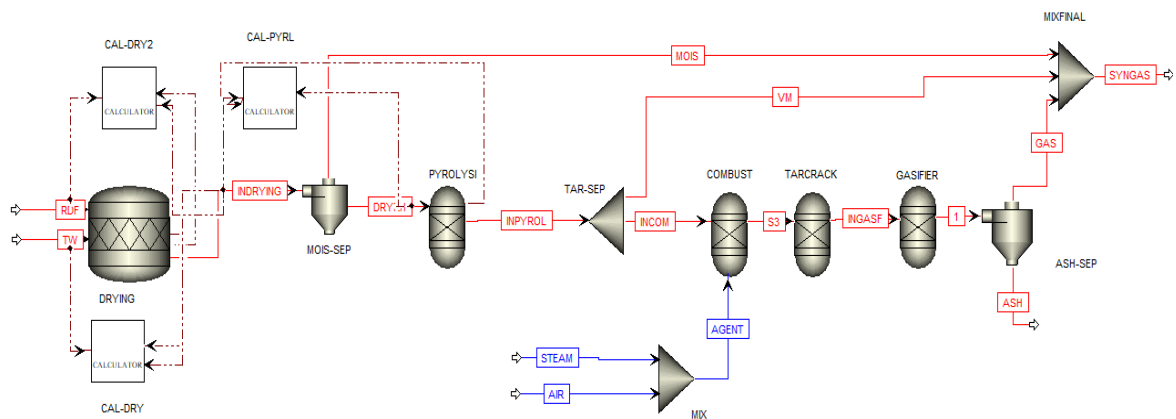


Figure 1: Aspen plus flowsheet of the co-gasification RDF and TW model

Table 2: Simulation Parameters for co-gasification RDF and TW

Block	Module	Describe and Reaction	ref
DRYING	RStoic	Simulates drying by quantifying water removal from RDF and TW based on reaction equations (Eq(2) and Eq(3)).	-
		WT \rightarrow 0.0709 H ₂ O	(2)
		RDF \rightarrow 0.0552 H ₂ O	(3)
MOIS-SEP	SSplit	Separates water from the feed stream after drying	-
		NC split fraction = 1	(4)
PYROLYSI	RYield	Simulates pyrolysis/devolatilization of RDF and TW, with products like H ₂ , N ₂ , O ₂ , H ₂ O, S determined by mass yield coefficients (Eq(5) - Eq(9)).	-
		C (CISOLID) \rightarrow 0.9619	(5) (Parthasarathy
		H ₂ \rightarrow 0.1405	(6) and Sheeba,
		N ₂ \rightarrow 0.0108	(7) 2015)
		O ₂ \rightarrow 0.3908	(8)
		H ₂ O \rightarrow 0.7262	(9)
COMBUST	RGibbs	Simulates combustion process assuming equilibrium reactions.	-
		Simulates tar cracking reactions during gasification, with reactions defined (Eq(10) - Eq(17)).	-
TAR-SEP	FSplit	C ₁₀ H ₈ + 4H ₂ O \rightarrow C ₆ H ₆ + 4CO + 5H ₂	(10)
		C ₁₀ H ₈ + 4.75H ₂ \rightarrow 1.25C ₆ H ₆ + 2.5CH ₄	(11)
		C ₇ H ₈ + H ₂ \rightarrow C ₆ H ₆ + CH ₄	(12) (Babatabar, and
		C ₆ H ₆ + 5H ₂ O \rightarrow 5CO + 6H ₂ + CH ₄	(13) Saidi, 2021)
		C ₈ H ₁₀ + 2H ₂ O \rightarrow C ₆ H ₆ + 2CO + 4H ₂	(14)
		C ₆ H ₆ O \rightarrow CO + 0.4C ₁₀ H ₈ + 0.15C ₆ H ₆ + 0.1CH ₄ + 0.75H ₂	(15)
		C ₉ H ₈ + 3H ₂ O \rightarrow C ₆ H ₆ + 3CO + 4H ₂	(16)
		C ₆ H ₆ O + 3H ₂ O \rightarrow 4CO + 2CH ₄ + 2H ₂	(17)
		Simulates combustion and gasification processes assuming equilibrium reactions.	-
		C + CO ₂ \rightarrow 2CO	(18)
GASIFIER	RGibbs	C + H ₂ O \rightarrow CO + H ₂	(19)
		C + 2H ₂ O \rightarrow CO ₂ + 2H ₂	(20) (Babatabar, and
		C + 2H ₂ \rightarrow CH ₄	(21) Saidi, 2021)
		H ₂ + S \rightarrow H ₂ S	(22) (Sierra et al.,
		CO + H ₂ O \rightarrow CO ₂ + H ₂	(23) 2021)
		CH ₄ + H ₂ O \rightarrow CO + 3H ₂	(24)
		C + O ₂ \rightarrow CO ₂	(25)
		C + 1/2O ₂ \rightarrow CO	(26)
ASH-SEP	SSplit	Separates ash from the feed stream after pyrolysis.	-
		CISOLID split fraction = 1	(27)
		NC split fraction = 1	(28)

The key reactions considered were the drying, pyrolysis, and gasification reactions, with their stoichiometric coefficients determined based on the feedstock composition and gasifying agent, all reactions have been described from Eq(2) to Eq(28).

The simulation parameters were set to investigate the effects of varying steam and air flows and temperature on the syngas composition, LHV, and CGE.

2.3 Calculation formula

The lower heating value of syngas (LHV_{syngas}) is the caloric of the syngas product calculated by the heat multiplied by the composition of the component gases (Le Tan et al., 2022). LHV_{syngas} was determined by Eq(29).

$$LHV_{syngas} = 10.7H_2 \% + 12.6.CO \% + 35.8CH_4 \% (MJ/kg) \quad (29)$$

Cold gas efficiency (CGE) is the percentage of the energy of syngas at standard temperature conditions compared to the energy of biomass in theory. CGE was calculated in Eq(30) (Shahadat Hossain, 2022).

$$CGE = \omega(LHV_{syngas}/LHV).100 (\%) \quad (30)$$

Where ω is the weight of syngas production (including the weights of the gases CO, CH₄, and H₂) per the dry mixed RDF and TW.

3. Results and discussions

3.1 Effect of Gasification Temperature on Co-gasification of RDF and TW

The gasification temperature exerts a significant influence on the syngas composition, lower heating value (LHV, in MJ/kg, and CGE during the co-gasification of RDF and TW (Figure 2 and Figure 3).

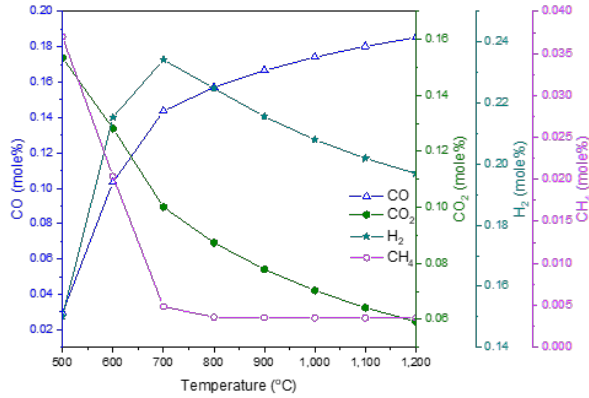


Figure 2: Syngas composition (mole%) at different gasification temperatures with 2 kg/h stream flow and 2 kg/h air flow

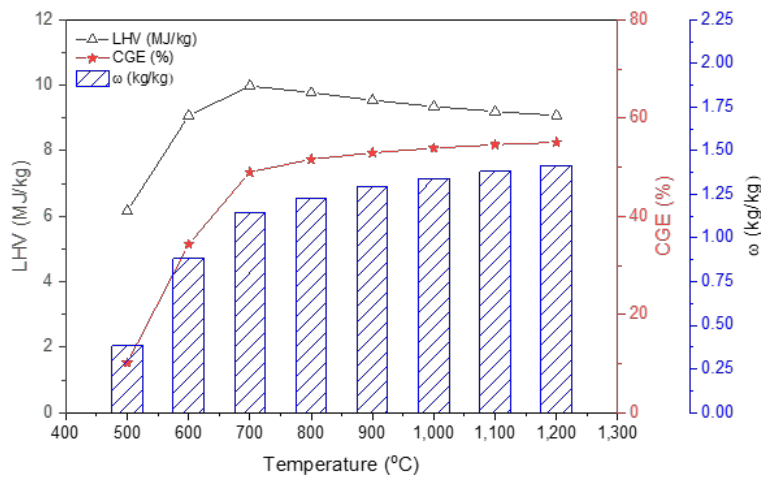


Figure 3: LHV, and CGE at different gasification temperatures with 2 kg/h stream flow and 2 kg/h air flow

The simulation results highlight the significant influence of temperature on syngas composition, LHV, CGE, and ω during the co-gasification process of RDF and TW. As temperature increases from 500 °C to 700 °C, the volume fractions of desirable combustible gases CO and H₂ rise substantially, reaching maximum of 0.14 and 0.23 mole% at 700 °C. The mole fractions of CO₂ and CH₄ decrease from 0.15 to 0.10 and 0.037 to 0.0048 mole% over this temperature range. This behavior stems from favorable high-temperature gasification reactions like water-gas shift, methane reforming, and Boudouard reactions promoting CO and H₂ formation while consuming CO₂, CH₄, and solid carbon. The LHV and CGE mirror this trend, peaking at 9.98 MJ/kg and 48.98 % at 700 °C due to increased combustible gas concentrations before declining at higher temperatures from excessive oxidation. Moreover, the syngas production weight (ω) shows a continuous rise from 0.38 kg/kg at 500 °C to 1.41 kg/kg at 1,200 °C (Figure 3), indicating higher solid-to-gas conversion at elevated temperatures. Ultimately, 700 °C emerges as the optimal temperature balancing syngas quality, energy density, process efficiency, and production yield during RDF and TW co-gasification.

3.2 Effect of Gasifying Agents on co-gasification RDF and TW

The Figure 4 presents the effect of varying the steam flow and air flow on the syngas composition, LHV, and CGE during the co-gasification of RDF and TW in a gasifier at 700°C.

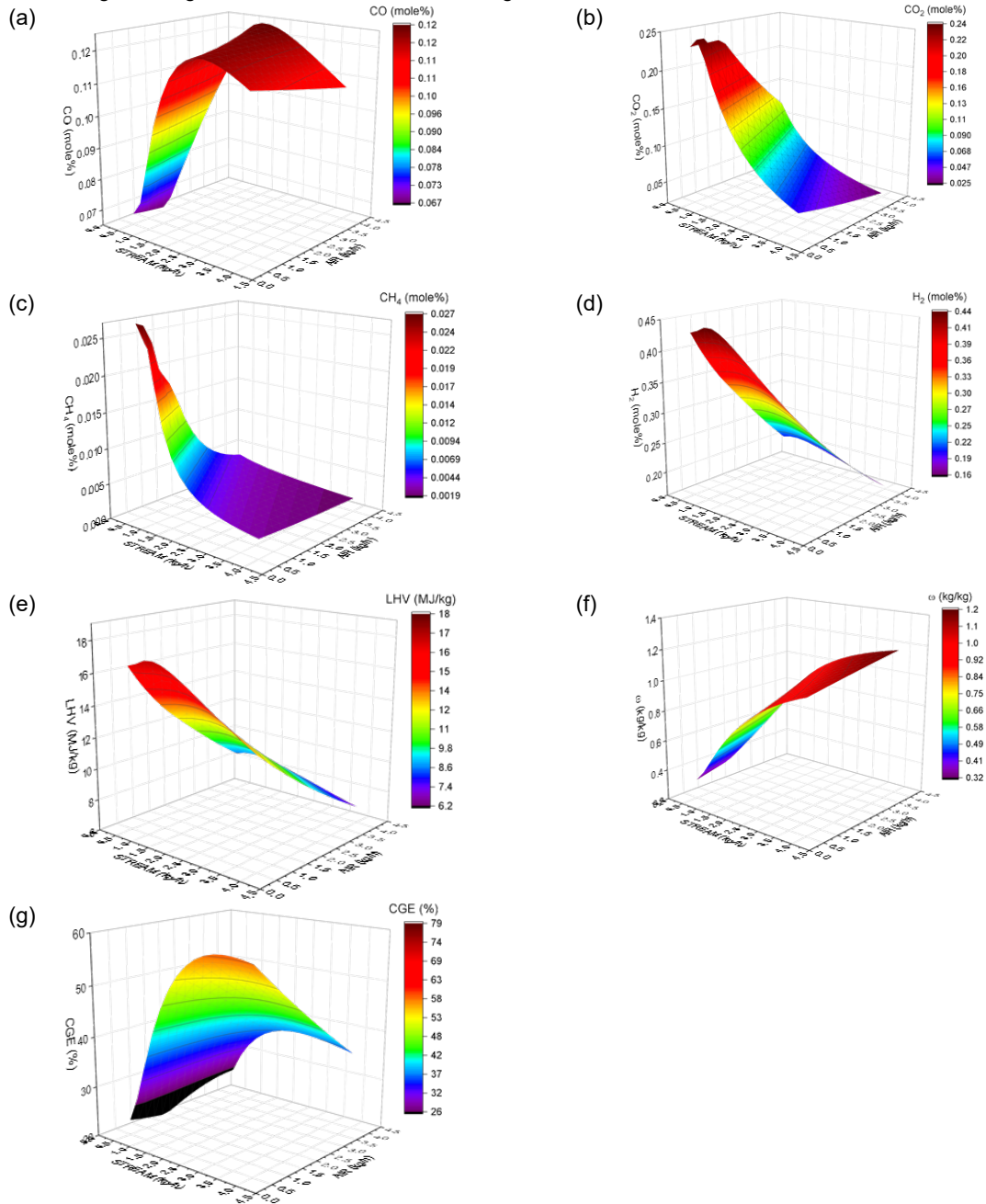


Figure 4: Effects of Steam Flow and Air Flow on Syngas Composition and Performance Metrics during Co-Gasification of RDF and TW. (a) CO Composition, (b) CO₂ Composition, (c) CH₄ Composition, (d) H₂ Composition, (e) LHV, and (f) ω and CGE

As the steam flow rate increases, the mole fractions of CO and H₂ in the syngas increase due to the promotion of the water-gas shift reaction (Eq(23)) and steam reforming reactions (Eq(24)). At an air flow rate of 0.5 kg/h, the CO mole fraction rises from 0.21 to 0.27 mole% as the steam flow rate increases from 0.5 to 2 kg/h, while the H₂ mole fraction increases from 0.41 to 0.47 mole% over the same range. The air flow rate increases, the mole fractions of CO and H₂ initially rise due to the partial oxidation of the feedstock, promoting reactions like Eq(25) and Eq(26). Beyond a certain air flow rate, the mole fractions start decreasing as the excess air oxidizes more CO and H₂ to CO₂ and H₂O. This trend is evident at a steam flow rate of 1.5 kg/h, where the CO mole

fraction increases from 0.14 to 0.20 mole% as the air flow rate increases from 0.5 to 1 kg/h, but then decreases to 0.05 mole% as the air flow rate further increases to 4 kg/h.

The LHV, CGE, and weight of syngas production (ω) are also influenced by the steam and air flow rates. An optimal condition of 0.5 kg/h steam flow rate and 0.5 kg/h air flow rate, where the LHV reaches a maximum value of 17.62 MJ/kg, the CGE peaks at 75.38 %, and ω is 1.28 kg/kg. This operating condition balances the formation of combustible gases (CO, H₂, and CH₄) with minimizing carbon losses, resulting in a high-quality syngas with balanced energy density, process efficiency, and production yield. Assuming typical syngas densities and using the provided mole fractions, the maximum LHV of 17.62 MJ/kg corresponds to approximately 14.5 MJ/Nm³. In comparison, Juma Haydary et al. (2023) reported lower heating values of 8.26 MJ/Nm³ for the dry gasification of RDF and 11.09 MJ/Nm³ for the wet gasification method. Gang Xiao reported LHV ranges of 4,000–9,000 kJ/Nm³ (4.0–9 MJ/Nm³) for the gasification of tire waste (Xiao et al., 2008). The co-gasification process in this study achieves a significantly higher LHV of approximately 14.5 MJ/Nm³, highlighting the advantages of co-gasifying RDF and TW in terms of syngas quality compared to their separate gasification.

4. Conclusions

Co-gasification of RDF and TW at the identified optimal temperature and steam/air flow rates achieved a significantly higher lower heating value and cold gas efficiency compared to separate gasification of RDF and TW. The balanced operating conditions produced a high-quality, energy-dense syngas (LHV of approximately 14.5 MJ/Nm³), clearly demonstrating the superior syngas quality attainable through co-gasification. These findings highlight the promising potential of co-gasification as a sustainable energy production route.

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