Environmental Health Engineering and Management Journal. 2025;12:1382
http://ehemj.com
doi 10.34172/EHEM.1382
Environmental Health Engineering and Management Journal

Original Article

Open Access Publish Free

Performance assessment of municipal solid waste operated modified downdraft gasifier for variations of air input and preheated air temperature

Kapil Dev Sharma[1*], **Siddharth Jain**[2]

[1]Department of Mechanical Engineering, Veer Madho Singh Bhandari Uttarakhand Technical University, Dehradun, Uttarakhand, India
[2]Mechanical Cluster, University of Petroleum and Energy Studies (UPES), Dehradun, Uttarakhand, India

Abstract

Background: Many municipal solid wastes (MSWs) produced worldwide can be used as an alternative to fossil energy. Synthetic gas produced from gasification of MSW can be used as fuel gas in various applications.

Methods: It deals with the performance assessment of a modified downdraft gasifier using MSW RDF pellets as feedstock under different equivalence ratios (ERs), air ratios (ARs), and preheated air temperatures (PATs). The effect of distinct values of ER, AR, and PAT on the cold gas efficiency (CGE), carbon conversion efficiency (CCE), and the concentrations of the syngas components were determined.

Results: The optimum values of ER and AR for unheated air were 0.4 and 0.66, respectively, which have been tested for the effect of PAT (from 100 to 210 °C). It was found that air preheating improved the performance of the gasification process, in which the percentage of the flammable gases increased CO (from 17.3% to 26.2%), H_2 (from 14.6% to 22.2%), and CH_4 (from 1.75% to 1.85%) compared to non-preheating air. Preheating of air also increased the value of LHV (from 4600 to 6053 kJ/kg). The CGE and CCE were increased from 68 to 69% and 85 to 93%, respectively, at the preheating temperature of 210 °C.

Conclusion: The results of this study can be used to optimize the performance of multistage gasifiers using air preheating and multistage air inlets.

Keywords: MSW, Gasification, RDF, Gasifier, Multistage

Citation: Sharma KD, Jain S. Performance assessment of municipal solid waste operated modified downdraft gasifier for variations of air input and preheated air temperature. Environmental Health Engineering and Management Journal. 2025;12:1382. doi: 10.34172/EHEM.1382.

Article History:
Received: 5 July 2024
Revised: 22 September 2024
Accepted: 1 October 2024
ePublished: 11 February 2025

***Correspondence to:**
Kapil Dev Sharma,
Email: kapildevsharmagkv@gmail.com

Introduction

Sustainable energy supply and proper solid waste disposal have always been global challenges that require constant research and development (1). Humans generate millions of tons of waste yearly, so adequate waste disposal has become a major issue worldwide. Municipal solid waste (MSW) is considered a renewable source in most countries because it is a never-ending source of energy generation (2-5). Waste to energy (WtE) is an innovative mechanism for extracting energy from solid waste and reducing the amount of waste on land. The energy generated from the waste can be used to meet the rapidly increasing energy needs worldwide (6-9). Therefore, WtE helps in reducing the problem of energy crisis, and also, in properly managing solid waste. Presently, the world is generating 2.01 billion tons (0.74 kg/person/day) MSW annually and it is projected that this production will reach around 3.40 BT by 2050 (10). There are various waste treatment technologies available in which the gasification of MSW is an attractive WtE process used presently to produce fuel (syngas) from MSW treatment (6).

Gasification involves the partial oxidation of organic or fossil-based carbonaceous material at high temperatures (500 to 1800 °C) in the presence of limited amounts of air. The first stage produces methane and charcoal, followed by the decomposition of charcoal into CO and H_2 (1,11-15). Gasification has excellent performance as compared to other WtE technologies i.e., less pollution and water are needed to clean the gas than direct incineration, predominant formation of CO rather than CO_2, requires less handling space compared to anaerobic digestion (AD), as well as fuel flexibility (16). A medium gasifier coupled with an internal combustion engine can meet all the energy needs of a small village (17). Gasification is a thermochemical conversion process of organic substances at high temperatures (500 to 1800 °C) in the presence of a limited amount of air (20- 35% of complete combustion) and gasification agent (mostly steam) to produce the syngas (mainly mixture of CO, H_2, and CO_2) (1,18). There are several types of gasifiers, such as down-draft, up-draft, cross-draft, fluidized bed and fixed bed gasifiers. Fixed-bed and fluidized-bed gasifiers have several disadvantages, such as low rates of feedstock conversion, low calorific value, and high tar yield, due to the use of low reaction temperatures. Downdraft gasifiers have many advantages over other types of gasifiers, including low dust and tar content, small in size, easy fabrication, high carbon conversion rate, ease of control, and multi-fuel flexibility (19–22). Refuge-derived fuel (RDF) refers to the high calorific non-recyclable segregated fraction of MSW. Segregated waste is compressed in the form of pellets or bricks that can effectively be used as fuel in gasifiers to generate syngas (13).

The gasification process has many operation and performance parameters such as equivalence ratio (ER), tar content, air ratio (AR), preheated air temperature (PAT), reactor temperature, residence time, the heating value of the syngas, cold gas efficiency (CGE), and carbon conversion efficiency (CCE). ER is defined as the ratio of the actual fuel/air ratio during gasification and the stoichiometric fuel/air ratio during complete combustion (12,16,23,24), where the ratio of the amount of air injected into the pyrolysis and oxidation zones is known as AR. During the experiment on the modified downdraft gasifier, the effect of different ER (0.30 to 0.50) for each AR (0.43 to 1) has been recorded without preheated air. After obtaining the optimum values of ER and AR, these values were tested with different temperatures of preheated air (100, 150, 180, and 210 °C).

Therefore, this paper is partitioned into two portions. Section 1 deals with the collection and segregation of MSW samples to be compressed in the form of pellets (RDF) followed by testing to check the suitability of the RDF waste within the gasification process to generate syngas. Section 2 is related to the performance assessment of a modified downdraft gasifier using MSW RDF pellets for different ER, AR, and PAT, which have not been done earlier in any research.

Materials and Methods

Study area and sampling

This study was carried out at the Haridwar city of India, which is the second-largest city in the Uttarakhand State in terms of population after Dehradun city. Haridwar is the second-largest district in the state of Uttarakhand, with a total land area of around 2,360 km^2. It is located at 314 meters above sea level, its latitude and longitude are 29.96°N and 78.15°E, respectively (25). The location of the MSW dumpsite in the city of Haridwar is close to the Sarai village, Bhagtanpur, with coordinates of Latitude: 29.9008 and Longitude: 78.092943 and a land area of 50.50 hectares. Thirty municipal wards in Haridwar city produce an average of 250 metric tons of MSW every day, most of which are discarded in the open at the Sarai Village Dump Site. During the experiment, a detailed compositional analysis of MSW from Haridwar city was carried out, which revealed that the MSW of the city contained almost all the components of the solid waste stream. The major components of the MSW stream were organic (49%), plastic (11%), paper (10%), textile (5%), glass (4%), metal (4%), inert and others (17%).

According to ASTM D5231-92, a total of 10 MSW samples (5 kg each) have been collected from 10 different strata of the Sarai village dumping site. After mixing all the samples, manual sorting was done to segregate the collected MSW into organic, inorganic, and recyclable categories.

Material of feedstock

In this experiment, RDF pellets have been used as a feedstock in a downdraft gasifier. High-calorific value combustible MSW components such as plastic and biodegradable were treated by shredding and dehydrating to produce RDF (26). The ASTM E829 and ASTM E828 standard methods have been used to prepare laboratory-scale RDF samples and determine the size of RDF pellets, respectively. RDF pellets were prepared with a diameter of 8–10 mm, a length of 25–30 mm, and a density of 1020 kg/m^3 with a moisture content not exceeding 5% as shown in Figure 1 (27).

The results of the Proximate analysis performed on the SDLA718 proximate analyzer according to ASTM D121 method, the ultimate analysis on the CHNSO analyzer (Model no. FLASH EA 1112) according to ASTM D3176-84 method (28), and calorific value on Leco AC-350 bomb calorimeter (29) are shown in Table 1. The substantial carbon content and high calorific value show that the produced MSW pellets are suitable for the gasification process.

Modification in existing downdraft gasifier

In the existing gasifier normal air was supplied only in the oxidation zone whereas in the modified gasifier preheated air (100 to 210 °C) has been supplied in both the pyrolysis and the partial oxidation zone. This resulted in the supply of more air to the gasifier as well as an increase in temperature in the pyrolysis zone, hence increasing the percentage of CO and decreasing the amount of tar content in the syngas. The line diagram of the existing gasifier apparatus and its modified form both are shown in Figure 2.

Gasification set-up

The gasification experiment was conducted using MSW RDF through a modified downdraft gasifier in which pre-heated atmospheric air was used as the gasification

Figure 1. RDF pellets Prepared from MSW

Table 1. The Characteristics of MSW RDF

Characteristics	
Proximate analysis (wt.%)	
Moisture	4.15
Volatile matter	82.5
Fixed carbon	8.85
Ash	4.5
Calorific value and density	
Calorific value (MJ/kg)	22.3
Density (kg/m³)	1020
Ultimate analysis (wt.%)	
Carbon	61.3
Hydrogen	8.8
Oxygen	26.6
Nitrogen	1.1
Sulfur	0.6
Phosphorus	0.7
Potash	0.9

medium. The existing gasifier was working on a single stage in which the inlet of the air was only in the oxidation zone but the modified gasifier works multistage with air inlet into both the pyrolysis and oxidation zone. A heater with adjustable temperature is installed just after the blower to heat the air coming from the blower. The material used for the wall of the gasifier was stainless steel while the insulating cement material was used on the inner layer of the gasifier to reduce the rate of heat transfer. A total of six K-type thermocouples are used to measure the temperature of the gasifier set-up, four of which are mounted on the gasifier wall to measure the temperature inside all four zones of the gasifier, one in the air one to measure the PAT, and one to measure the temperature of the generated syngas. In single-stage operation, the pyrolysis zone valve is completely closed, while in multistage operation, the pyrolysis and oxidation zone valves are opened at different ARs to control the volume of air entering. Single and multi-stage operations were performed by adjusting the valve opening of the oxidation and pyrolysis zones. In the single-stage situation, the air valve for the pyrolysis zone was completely closed but the valve for the oxidation zone was open, while for the multistage both the oxidation and pyrolysis air valves were kept open. The gasification system consists of a gasifier, cyclone, screw conveyor, heater, blower, gas filter, and sensors as shown in Figure 3.

Experiment on gasifier set-up

Ten kilograms of RDF was placed over the burning charcoal on the top of the gasifier to drive the system at the beginning of the experiment. The experiment was divided into two phases, one for preheated air and the other for multistage. The multistage experiment was performed by supplying different ARs of 30:70 (0.43), 40:60 (0.66), and 50:50 (1.0) to the partial pyrolysis and oxidation regions of the gasifier without preheated air. The ER for the single stage has also been varied by 0.3, 0.4, and 0.5. The optimum value of ER was obtained during the experiment for a single stage, after which the optimum value for AR was also obtained after testing the optimum value of ER at different AR values. The optimum values of ER and AR were again tested with different temperatures (100, 150, 180, and 210 °C) of preheated air to note down the effect of preheated air on the gasification process. Variation of ER and AR without preheated temperature is shown in Table 2.

Cold gas and carbon conversion efficiency

CGE has been defined as it is the ratio of the heating value of the produced syngas and the heating value of the fuel (solid waste), calculated using Eq. (1).

$$\mathrm{CGE}(\%)=\frac{\left(\boldsymbol{Q}_{syngas}\times \boldsymbol{LHV}_{syngas}\right)}{\left(\boldsymbol{Q}_{RDF}\times \boldsymbol{LHV}_{RDF}\right)}\times 100 \qquad (1)$$

In equation (1), Q_{syngas} (Nm³/hr) is the generation rate of syngas, Q_{RDF} is the feed rate of RDF (kg/hr), LHV_{syngas} and LHV_{RDF} are the lower heating value of Syngas and RDF in kcal/Nm³. In this equation, $\mathrm{LHV}_{\mathrm{Syngas}}$ has been calculated

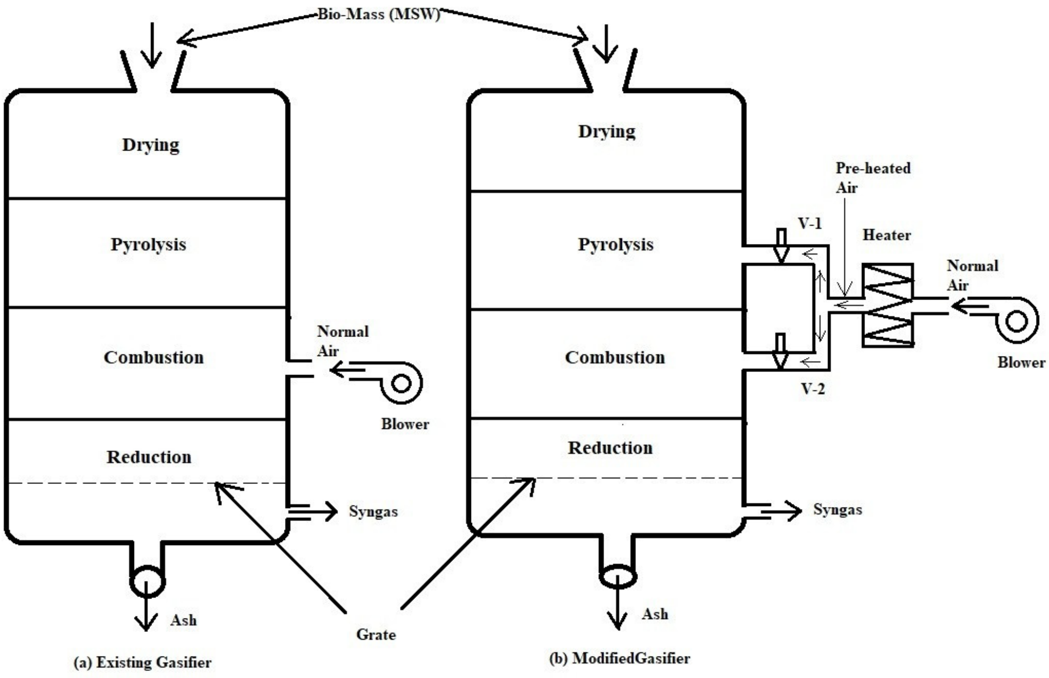


Figure 2. Modification of existing gasifier

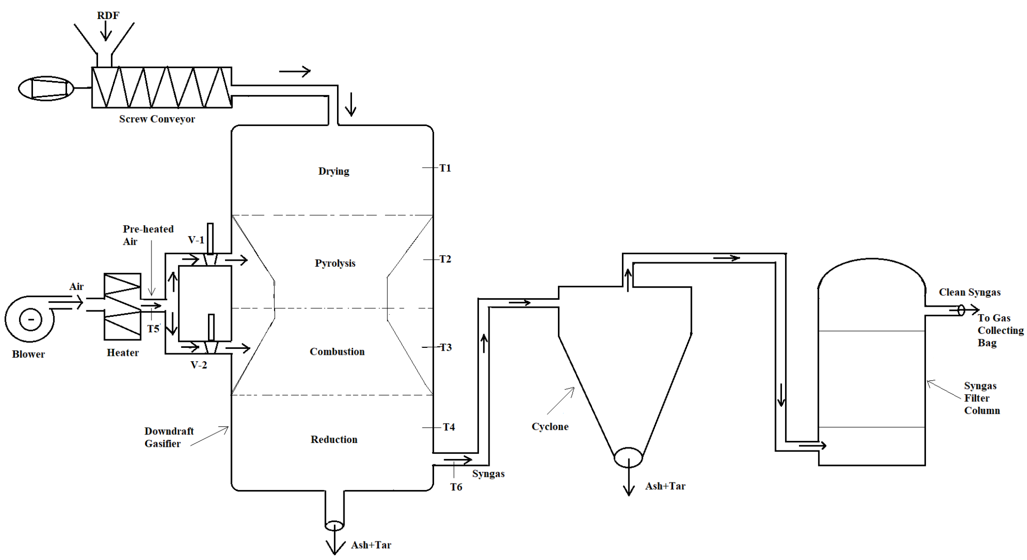


Figure 3. Modified gasifier set-up

using Eq. (2).

$$\text{LHVSyngas} = \frac{(\boldsymbol{H_2\%}\times 11.2)+(\boldsymbol{CO\%}\times 13.1)+(\boldsymbol{CH_4\%}\times 37.1)}{100} \quad (2)$$

Where H_2, CO, and CH_4 are the percentage composition of Hydrogen, Carbon Monoxide, and Methane in generated syngas, calculating by GAS 3100 gas component analyzer.

The flow rate of the air also affects the quality of the generated syngas, which was determined in kg/h using Eq. (3).

$$Ma = \left[\frac{32\times C}{12} + 8\times H + S - O\right] \times ER \times Q_{RDF} \quad (3)$$

Where, C, H, S, and O are the results of the fraction of percentage, carbon, hydrogen, sulphur, and oxygen, calculated by the ultimate analysis.

CCE refers to how much carbon in solid waste, such as CO, CO_2, CH_4, C_2H_2, C_2H_4, and C_2H_6, is converted into syngas, which is calculated using Eq. (4).

$$CCE(\%) = \frac{(\boldsymbol{Q_{syngas}} \times \boldsymbol{C_{syngas}})}{(\boldsymbol{Q_{RDF}} \times \boldsymbol{C_{RDF}})} \times 100 \quad (4)$$

Table 2. Variation of ER and AR without preheated air

ER	AR	Air flow rate (Nm^3/h)		
		Pyrolysis	Oxidation	Total
	AR1 (0.43)	4.95	11.55	16.50
0.3	AR2 (0.66)	6.6	9.9	16.50
	AR3 (1.00)	8.25	8.25	16.50
	AR1 (0.43)	6.72	15.68	22.4
0.4	AR2 (0.66)	8.96	13.44	22.4
	AR3 (1.00)	11.2	11.2	22.4
	AR1 (0.43)	8.34	19.46	27.8
0.5	AR2 (0.66)	11.12	16.68	27.8
	AR3 (1.00)	13.9	13.9	27.8

Where C_{syngas} and C_{RDF} are fractions of carbon in syngas and RDF, respectively.

The potential of energy production through gasification

Total MSW generated per day in Haridwar city: 250 tons

Average moisture content on a wet basis = 28%

Total dry MSW generated per day in Haridwar city: 250*(100-28)/100 = 180 tons

Percentage of combustible and non-organic waste in MSW on a dry basis: 25%

MSW energy potential for Haridwar city

(a) In terms of electricity generation from MSW

Total combustible and non-organic MSW generated = (25 × 180) /100 = 45 ton/day = 45×10^3 kg/day

Total RDF weight prepared from MSW: 45×10^3*(100-4.15)/100 = 43×10^3 kg/day

Typical calorific value of RDF = 22.3 MJ/kg

Approx. power generation potential = $(22.3 \times 43 \times 10^3)/86\,400 = 11$ MJ/Sec = 11 MW

So, it can be predicted that the energy potential of combustible and non-organic waste is around = 11 MW.

(b) In terms of Syngas production from MSW

The average syngas yield for (ER:0.4, and AR:0.66) = 2.5 Nm^3/kg = 2.7 m^3/kg

Total syngas generated = $45 \times 10^3 \times 2.7 = 121\,500$ m^3/day

Lower heating value (LHV) of syngas = 6.05 MJ/m^3

And energy content of syngas = 305 100 × 5.8 = 735 075 MJ/day

Comparison of NOx emission for Haridwar city

(a) Emission of NOx from MSW of Haridwar city

The average syngas yield for (ER:0.4, and AR:0.66) = 2.5 Nm^3/kg = 2.7 m^3/kg

So, total syngas generated = $45 \times 10^3 \times 2.7$ = 1,21,500 m^3/day

NOx generated by burning of 1 m^3 of syngas = 0.0315 g/m^3

Total amount of NO_x generated by burning of syngas per year = 1,148 kg/year (if the plant runs 300 days in a year)

(b) Emission of NOx from conventional thermal power plant

NO_x liberated in a coal power plant = 4.30 g/kWh

Amount of NO_x liberated per day = 4.30 × 27870 × 24 = 1 135 200 g/day

The total amount of NO_x liberated per year = 862 855 kg/year (if the plant runs 300 days in a year)

So, Equivalent saving of NO_x = 340 560-1148 = 339 412 kg/year

Techno-economic analysis for gasification of MSW

Techno-economic analysis of the combustible and inorganic fractions of MSW of Haridwar city is shown in Table 3. The payback period of the plant for different per-day quantities of solid waste is presented. The capital, operating, and maintenance costs for different capacities show that the payback period was 5.17 to 5.5 years for per-day quantities of 1 to 10 tons, respectively.

Results

The ER value was scaled between 0.3 to 0.5 to determine the effect on syngas composition, CCE, and CGS at the normal incoming air temperature.

The optimum value of ER was found to be 0.4. The value of AR was also scaled from 0.43 to 1 to determine the effect on syngas LHV and composition for the optimum value of ER (0.4) without preheated air. The optimum value of AR for ER 0.4 was fond AR2 (0.66), which significantly impacts gasification performance.

The effect of PAT concerning changes in fuel composition, LHV, gas yield, CCE, and CGE has been calculated for the optimum values of ER and AR. The temperature variation within the gasifier concerning change in PAT and ER has also been calculated.

It was found that air preheating is more effective at lower ER, hence preheating should not be used for ER above 0.4. The maximum values of CGE and CCE without preheating reached 68% and 85%, respectively. After preheating, CGE and CCE increased to 69% and 93%, respectively. When comparing AR and ER, the most effective way to improve performance can be done through AR.

The temperature distribution inside the gasifier for different PAT and ER values at the fixed value of AR of 0.66.

The increase in PAT is also responsible for increasing the temperature of each gasifier zone, which means that the temperature in the pyrolysis zone will increase, which causes a decrease in tar content.

Discussion

Effect of equivalence ratio

The results showed that the CO production increased but

Table 3. Techno-economic analysis for gasification of MSW

Parameter	Quantity				Units
Quantity of combustible and non-organic fractions of MSW per day	**1**	**2**	**5**	**10**	ton/day
Average syngas yield for (ER:0.4, and AR:0.66)	2700	2700	2700	2700	m^3/ton TS
If plant efficiency is 65%	1755	1755	1755	1755	m^3/ton TS
1 m^3 of biogas is equivalent to (30)	0.13	0.13	0.13	0.13	kg of LPG
Total LPG replacement per day	288	576	1140	2281	kg of LPG
Cost of 1 kg of LPG (Commercial) (30)	95.5	95.5	95.5	95.5	INR
Revenue from the plant per year (300 days)	8 251 200	16 502 400	32 661 000	65 350 650	INR
O & M cost of the plant per year (31)	1 100 000	2 310 000	4 800 000	12 000 000	INR
Net revenue from the plant for one year	7 151 200	14 192 400	27 861 000	53 350 650	INR
Capital cost of the plant with accessories (32)	37 000 000	77 750 000	166 500 000	296 000 000	INR
Simple payback period	5.17	5.47	5.97	5.5	Years

CO_2 decreased with an increase in ER. This decrease was due to an increase in the Boudouard reaction rate, which was affected by the increase in temperature. The reaction used CO_2 as a reactant, which produced more CO. On the other hand, an increase in ER increased oxygen concentration resulting in a decrease in H_2 and CH_4. The optimum value of ER was 0.4, which produced the highest flammable gases such as CO (17.3%), H_2 (14.6%), and CH_4 (1.75%) (Agilent Gas Chromatograph, Model: 6890N, Mass range:10-1000 amu), and the maximum production of LHV (4600 kJ/kg) was recorded. The effect of ER on CCE and CGE is shown in Figure 4a and 4b. CCE increased with an increase in ER, while CGE increased up to 0.3 ER and decreased thereafter. The value of CCE did not increase significantly from 0.4 to 0.5 ER while CGE decreased significantly for this range of ER. Therefore, the optimal value of ER was recorded as 0.4, which gave 85% CCE and 68% CGE. These optimum values of ER and AR were used as reference values for air pre-heating air operations.

Effect of air ratio

The comparison of results between single-stage and multi-stage gasification revealed that the optimal ER is 0.4. An increase in the value of AR shows that LHV also increased LHV from 4520 to 5410 KJ/kg. The percentage of CO and H_2 have been increased from 18.2% to 25.6% and 14.4% to 17.7%, respectively, as shown in Figure 5. Meanwhile, as the value ER increased, the reduction zone temperature increased but the CH_4 value decreased from 2.2% to 1.2% due to more air entering the partial oxidation zone. The percentage of CO_2 also decreases slightly because the carbon consumed in the Baudouard reaction was converted to CO. AR and ER, both equally affect the change of temperature distribution inside the gasifier such that when AR increases from 0.43 to 1.0 and ER increases from 0.3 to 0.5, each change inside the gasifier causes a temperature increase. The optimum value of AR was AR2 (0.66), which significantly impacts gasification performance.

Effect of preheated air temperature

The effect of PAT was recorded using thermocouples for ER of 0.4 and AR of 0.66. Temperature readings from the thermocouples showed an increase in temperature in each zone in the gasifier when preheated air was supplied from 100 to 210 °C. The reactor temperature was raised to 790–910 °C and 1034–1165 °C for the pyrolysis and oxidation zones, respectively. In addition, an increase in PAT led to an increase in the composition of flammable gases and LHVs. The percentages of CO and H_2 increased from 21.6% and 17.5% to 26.2% and 22.2%, respectively, while CH_4 increased only slightly from 1.38% to 1.85%, with the LHV increased from 5040 to 6035 kJ/kg during this period as shown in Figure 6a. The drying and pyrolysis increased H_2 production from H_2O in the product, while increasing CO production from volatiles. The effect of PAT on CCE and CGE is shown in Figure 6b. Both CCE and CEG increased when PAT increased. The increase rate of CCE at higher PAT decreased because of less CO_2 availability due to reduction reactions, while a proportional relationship was found between CGE and PAT. The highest values of CCE and CGE at PAT of 210 °C, AR of 0.66, and ER of 0.4 were 93% and 69%, respectively.

Effect of PAT and ER on the temperature inside the gasifier

The temperature distribution inside the gasifier with an AR of 0.66 for ER of 0.3, 0.4, and 0.5 was distributed in Figure 7a. The temperature of each gasification zone such as drying, pyrolysis, oxidation, and reduction increased when increasing the value of ER. This is because when increasing the value of ER also increases the amount of air entering the gasifier, which releases more heat energy during the oxidation reaction. This indicates that the lower ER makes the oxidation reaction more optimal. The oxidation reaction is exothermic in which more heat energy is released as the level of air increases. The effect of different temperatures (100, 150, 180, and 210 °C) of the

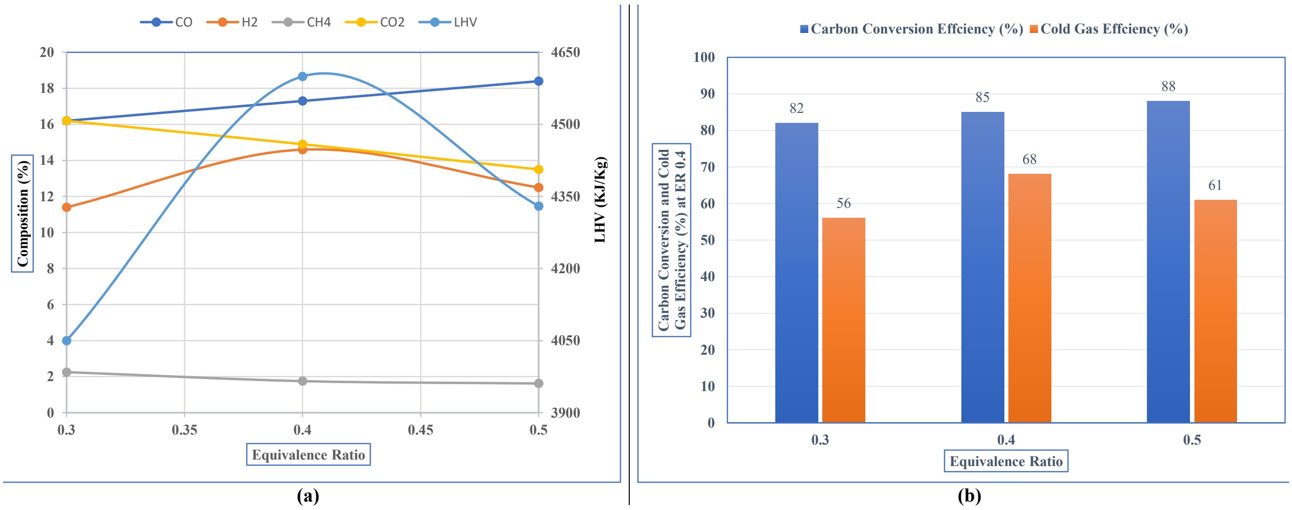


Figure 4. Effect of ER (a) on composition and LHV of syngas (b) on carbon conversion and cold gas efficiency

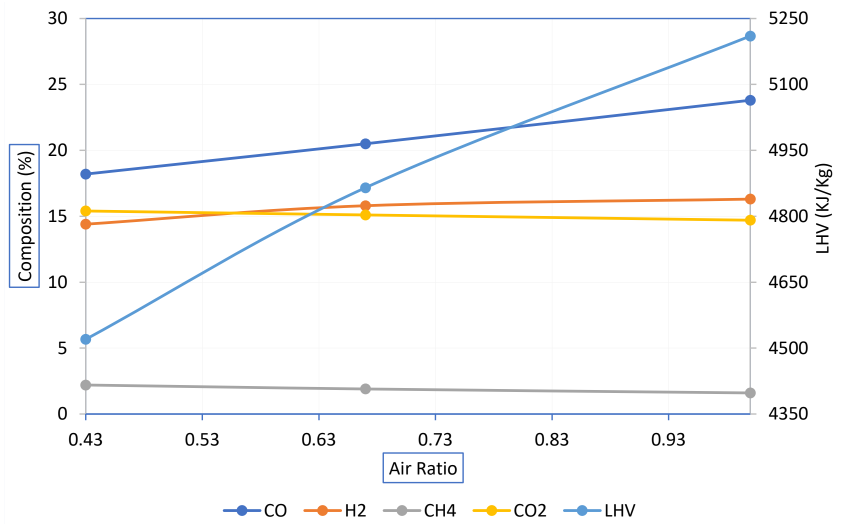


Figure 5. Effect of air ratio (AR) to the composition and LHV of syngas for the optimum value of ER (0.4)

preheated air is detailed in Figure 7b for the temperature distribution inside the gasifier with AR of 0.66 and ER of 0.4. When the PAT increased from 100 to 210°C, the pyrolysis and oxidation zones of the gasifier also showed a significant increase to 842–952 °C and 995–1165 °C, respectively.

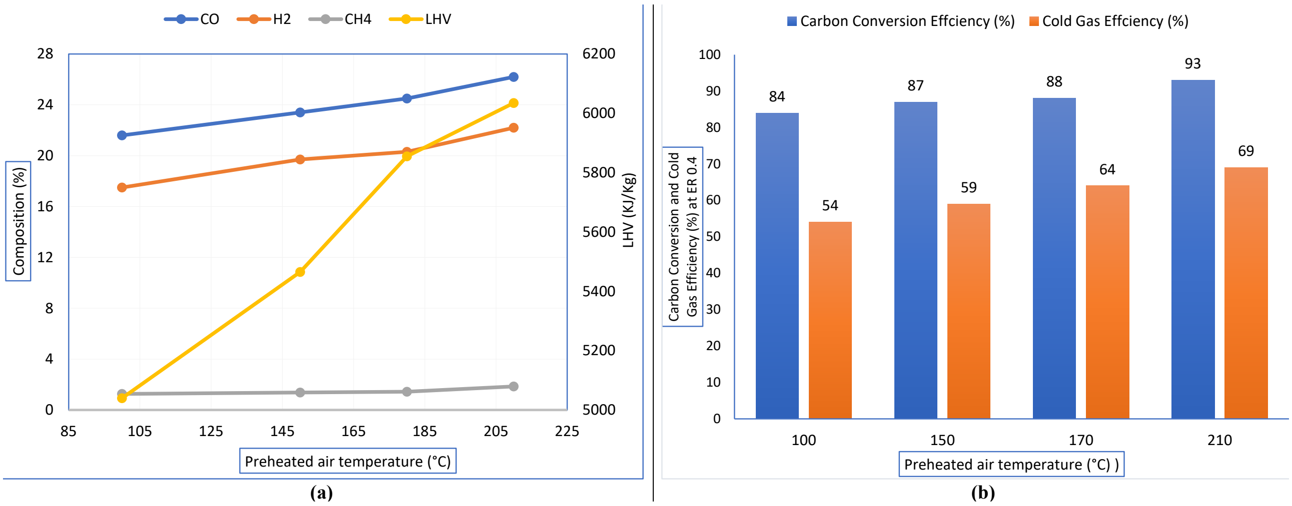
Conclusion

According to the results, the optimum values of ER and AR for unheated air were 0.4 and 0.66, respectively. When ER was increased, the temperature of each zone in the gasifier increased while on the other hand, the composition of flammable gas and LHV decreased. The maximum value of CGE and CCE reached 68% and 85% without preheating air, respectively. An increase in AR increased LHV from 4520 to 5410 kJ/kg, CO from 18.2% to 25.6%, and H_2 from 14.4% to 17.7%. However, when comparing AR and ER, the most effective way to improve performance can be done through AR.

Air preheating increases the production of combustible gases, H_2 and CO, which increases the syngas heating value and gasifier CGE. The increase in PAT is also responsible for increasing the temperature of each gasifier zone, indicating that there will be an increase in temperature in the pyrolysis zone, which causes a decrease in the tar content. The percentage of flammable gases has increased CO (from 17.3% to 26.2%), H_2 (from 14.6% to 22.2%), CH_4 (from 1.75% to 1.85%), and LHV (from 4600 to 6053 kJ/kg) compared to non-preheating air. The CGE and CCE increased from 68 to 69% and 85 to 93%, respectively, at the preheating temperature of 210 °C. Air preheating is found to be more effective at low ER, therefore, air preheating should not be used for ER above 0.4.

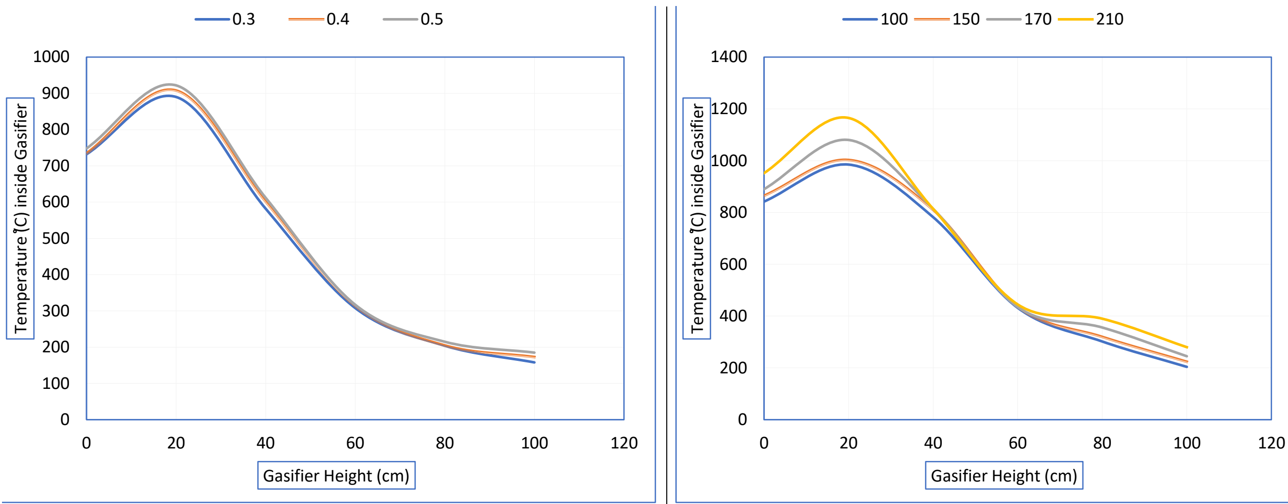
Acknowledgments

The authors are grateful to the Indian Academy of Environmental Sciences Hardwar and the Haridwar Nagar Palika Parishad (HNPP) for providing valuable



(a) (b)

Figure 6. Effect of PAT (a) on Composition and LHV of syngas for ER (0.4) and AR (0.66), (b) on Carbon Conversion and Cold Gas Efficiency for ER (0.4) and AR (0.66)



(a) (b)

Figure 7. The temperature inside the gasifier (a) at different PAT for ER (0.4) and AR (0.66) (b) at different Equivalence Ratio for PAT (210ºC) and AR (0.6)

solid waste information. They also express their gratitude to colleagues, friends, and organizations from all over the world who have provided valuable information.

Authors' contributions

Conceptualization: Kapil Dev Sharma.
Data curation: Kapil Dev Sharma.
Formal analysis: Kapil Dev Sharma.
Investigation: Siddharth Jain.
Methodology: Kapil Dev Sharma.
Project administration: Siddharth Jain.
Resources: Kapil Dev Sharma.
Supervision: Siddharth Jain.
Validation: Kapil Dev Sharma.
Visualization: Siddharth Jain.
Writing–original draft: Kapil Dev Sharma.
Writing–review & editing: Kapil Dev Sharma.

Competing interests

The authors declare that there are no competing interests.

Ethical issues

The author hereby certifies that all data collected during the study is as stated in the manuscript, and no data from the study have been or will be published separately elsewhere.

Funding

There is no funding information to declare.

References

1. Yang Y, Liew RK, Tamothran AM, Foong SY, Yek PN, Chia PW, et al. Gasification of refuse-derived fuel from municipal solid waste for energy production: a review. Environ Chem Lett. 2021;19(3):2127-40. doi: 10.1007/s10311-020-01177-5.
2. Azam M, Jahromy SS, Raza W, Raza N, Lee SS, Kim KH, et al. Status, characterization, and potential utilization of municipal solid waste as renewable energy source: Lahore case study in Pakistan. Environ Int. 2020;134:105291. doi: 10.1016/j.envint.2019.105291.
3. Chand Malav L, Yadav KK, Gupta N, Kumar S, Sharma

GK, Krishnan S, et al. A review on municipal solid waste as a renewable source for waste-to-energy project in India: current practices, challenges, and future opportunities. J Clean Prod. 2020;277:123227. doi: 10.1016/j.jclepro.2020.123227.
4. Alzate S, Restrepo-Cuestas B, Jaramillo-Duque Á. Municipal solid waste as a source of electric power generation in Colombia: a techno-economic evaluation under different scenarios. Resources. 2019;8(1):51. doi: 10.3390/resources8010051.
5. Khalil M, Berawi MA, Heryanto R, Rizalie A. Waste to energy technology: the potential of sustainable biogas production from animal waste in Indonesia. Renew Sustain Energy Rev. 2019;105:323-31. doi: 10.1016/j.rser.2019.02.011.
6. Chen H, Zhang M, Xue K, Xu G, Yang Y, Wang Z, et al. An innovative waste-to-energy system integrated with a coal-fired power plant. Energy. 2020;194:116893. doi: 10.1016/j.energy.2019.116893.
7. Margallo M, Ziegler-Rodriguez K, Vázquez-Rowe I, Aldaco R, Irabien Á, Kahhat R. Enhancing waste management strategies in Latin America under a holistic environmental assessment perspective: a review for policy support. Sci Total Environ. 2019;689:1255-75. doi: 10.1016/j.scitotenv.2019.06.393.
8. Mancini E, Arzoumanidis I, Raggi A. Evaluation of potential environmental impacts related to two organic waste treatment options in Italy. J Clean Prod. 2019;214:927-38. doi: 10.1016/j.jclepro.2018.12.321.
9. Rizwan M, Saif Y, Almansoori A, Elkamel A. Environmental performance of municipal solid waste processing pathways. Energy Procedia. 2019;158:3363-8. doi: 10.1016/j.egypro.2019.01.957.
10. Khandelwal H, Dhar H, Thalla AK, Kumar S. Application of life cycle assessment in municipal solid waste management: a worldwide critical review. J Clean Prod. 2019;209:630-54. doi: 10.1016/j.jclepro.2018.10.233.
11. Awasthi MK, Sarsaiya S, Chen H, Wang Q, Wang M, Awasthi SK, et al. Global status of waste-to-energy technology. In: Kumar S, Kumar R, Pandey A, eds. Current Developments in Biotechnology and Bioengineering. Elsevier; 2019. p. 31-52. doi: 10.1016/b978-0-444-64083-3.00003-8.
12. Bhavanam A, Sastry RC. Biomass gasification processes in downdraft fixed bed reactors: a review. Int J Chem Eng Appl. 2011;2(6):425-33.
13. Khosasaeng T, Suntivarakorn R. The gasification efficiency improving by self-steam gasifier using RDF from municipal solid waste. IOP Conf Ser Earth Environ Sci. 2019;257(1):012026. doi: 10.1088/1755-1315/257/1/012026.
14. Sadaka S. Gasification, Producer Gas and Syngas. Fayetteville: University of Arkansas, United States Department of Agriculture, and County Governments Cooperating; 2010. Available from: https://www.uaex.uada.edu/publications/PDF/FSA-1051.pdf.
15. de Menezes Neto JT, Alves AJ, Carvalhaes V. An efficiency study on the urban solid waste gasification process for electric power generation. In: 2017 18th International Scientific Conference on Electric Power Engineering (EPE). Kouty nad Desnou, Czech Republic: IEEE; 2017. p.1-6. doi: 10.1109/epe.2017.7967305.
16. Zhu L, Zhang L, Fan J, Jiang P, Li L. MSW to synthetic natural gas: system modeling and thermodynamics assessment. Waste Manag. 2016;48:257-64. doi: 10.1016/j.wasman.2015.10.024.
17. Upadhyay DS, Sakhiya AK, Panchal K, Patel AH, Patel RN. Effect of equivalence ratio on the performance of the downdraft gasifier – an experimental and modelling approach. Energy. 2019;168:833-46. doi: 10.1016/j.energy.2018.11.133.
18. Saleh AR, Sudarmanta B, Fansuri H, Muraza O. Improved municipal solid waste gasification efficiency using a modified downdraft gasifier with variations of air input and preheated air temperature. Energy Fuels. 2019;33(11):11049-56. doi: 10.1021/acs.energyfuels.9b02486.
19. Khosasaeng T, Suntivarakorn R. Effect of equivalence ratio on an efficiency of single throat downdraft gasifier using RDF from municipal solid waste. Energy Procedia. 2017;138:784-8. doi: 10.1016/j.egypro.2017.10.066.
20. Anis S, Nugroho B, Kusumastuti A. Design and preliminary testing of a small-scale throatless fixed-bed downdraft gasifier fueled with sengon wood block. J Adv Res Fluid Mech Therm Sci. 2024;80(1):1-12.
21. Fortunato B, Brunetti G, Camporeale SM, Torresi M, Fornarelli F. Thermodynamic model of a downdraft gasifier. Energy Convers Manag. 2017;140:281-94. doi: 10.1016/j.enconman.2017.02.061.
22. Ebrahimi A, Amin MM, Bina B, Mokhtari M, Alaghebandan HR, Samaei MR, et al. Prediction of the energy content of the municipal solid waste. Int J Environ Health Eng. 2012;1(6):1-6. doi: 10.4103/2277-9183.105344.
23. Doherty W, Reynolds A, Kennedy D. The effect of air preheating in a biomass CFB gasifier using ASPEN Plus simulation. Biomass Bioenergy. 2009;33(9):1158-67. doi: 10.1016/j.biombioe.2009.05.004.
24. Hashemi H, Pourzamani H, Rahmani Samani B. Comprehensive planning for classification and disposal of solid waste at the industrial parks regarding health and environmental impacts. J Environ Public Health. 2014;2014:230163. doi: 10.1155/2014/230163.
25. ECON Laboratory & Consultancy. Solid Waste Characterization Report for Environmental Baseline Study of Municipal Solid Waste Dumpsite Haridwar, Uttarakhand. 2019. Available from: https://udd.uk.gov.in/files/Solid_Waste_Characteristics_Haridwar.pdf.
26. Ministry of New and Renewable Energy (MNRE). Power Generation from Municipal Solid Waste. Lok Sabha Secretariat; 2016. p. 1-85. Available from: https://eparlib.nic.in/bitstream/123456789/65224/1/16_Energy_20.pdf.
27. Parvez N, Agrawal A, Kumar A. Solid waste management on a campus in a developing country: a study of the Indian Institute of Technology Roorkee. Recycling. 2019;4(3):28. doi: 10.3390/recycling4030028.
28. Bala R, Gautam V, Mondal MK. Improved biogas yield from organic fraction of municipal solid waste as preliminary step for fuel cell technology and hydrogen generation. Int J Hydrogen Energy. 2019;44(1):164-73. doi: 10.1016/j.ijhydene.2018.02.072.
29. Ibikunle RA, Titiladunayo IF, Akinnuli BO, Osueke CO, Dahunsi SO, Olayanju A. Impact of physical and chemical properties of municipal solid waste on its electrical power rating potential. J Phys Conf Ser. 2019;1299(1):012003. doi: 10.1088/1742-6596/1299/1/012003.
30. Wahyuni NL, Soeswanto B, Akmal H, Puspita N. Effect of particle size distribution and acid treated coal bottom ash on TSS and COD removal from textile effluent using

fixed bed column. IOP Conf Ser Earth Environ Sci. 2018;160(1):012015. doi: 10.1088/1755-1315/160/1/012015.
31. Central Electricity Regulatory Commission (CERC). Determination of Levellised Generic Tariff for FY 2022-23 Under Regulation 8 of the Central Electricity Regulatory Commission. CERC; 2022. p. 1-220. Available from: https://cercind.gov.in/2022/whatsnew/Draft-RE%20Tariff%20Order-2022-23.pdf.
32. Satiada MA, Calderon A. Comparative analysis of existing waste-to-energy reference plants for municipal solid waste. Clean Environ Syst. 2021;3:100063. doi: 10.1016/j.cesys.2021.100063.