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Article

Analysis of Thermal Properties in Co-Gasification of Municipal Solid Waste and Woody Biomass

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Abstract: Modern downdraft gasifiers used commercially are predominantly tailored for efficiently converting woody biomass, such as wood chips. However, substantial value also lies in the utilization of wood residues and Municipal Solid Waste (MSW), which are often underexploited. For gasifiers to serve a wider range of applications effectively, they must be capable of handling diverse waste inputs and adjusting their operation in real-time to suit varying material characteristics. This study centers on the advancement of a tar-free gasification system capable of processing MSW with high flexibility. The investigation outlines the systematic approach taken in designing, developing, and assessing the performance of this innovative gasifier. The core focus of the technology is to convert MSW into usable thermal energy through gasification. The prototype developed in this work features a square-shaped stratified fixed-bed downdraft gasifier, engineered to process up to 10 kg of feedstock per hour. It accommodates both pelletized and non-pelletized forms of MSW, offering versatility in input types. During experimental trials, the highest volume of producer gas 38 m^3/h. was recorded in the third trial phase, which utilized a balanced mixture of wood and MSW in equal proportions. This setup also yielded the highest calorific value of gas, calculated at 1250 kcal/Nm^3. By integrating advanced thermal flare systems that efficiently combust the produced gas, the developed gasifier significantly reduces thermal energy production costs. Furthermore, analyses of the mass and energy distribution confirmed an efficient and consistent relationship between the fuel input and the energy output, validating the system's operational effectiveness.

Keywords: municipal solid waste; woody biomass; down draft gasification

1. Introduction

The rapid growth in the consumption of goods and materials has led to a significant rise in municipal solid waste (MSW), posing a serious challenge to environmental protection and quality of life. MSW consists of a wide variety of discarded items, including metals, paper products, textiles, plastics, wood, and organic kitchen waste [1,2]. Municipal solid waste (MSW) management in India focuses not only on minimizing waste generation but also on ensuring effective treatment and maximizing recycling efforts. Oversight and regulation of waste management are primarily handled by various government bodies, including the Ministry of Environment, Forest and Climate Change (MoEFCC), the Ministry of Housing and Urban Affairs (formerly MoUD), the Central Pollution Control Board (CPCB), the National Environmental Engineering Research Institute (NEERI), and the respective State Pollution Control Boards (SPCBs). At the local level, the responsibility for on-ground implementation lies with Urban Local Bodies (ULBs). However, numerous studies have highlighted that ULBs often struggle to effectively enforce and manage MSW policies. Creating a robust and efficient MSW management framework requires aligning objectives with stakeholders' needs and expectations. The Government of India continues to support and encourage ULBs in enforcing regulations and applying relevant policies at the grassroots level. As of now, the revised Municipal Solid Waste (Management and Handling) Rules, 2015, are in the process of being finalized by the MoEFCC. According to the 2014 report by the Planning Commission of India, urban areas are home to approximately 377 million people, collectively generating around 62 million tonnes of MSW annually [3,4]. Urban centers are expected to produce about 165 million tonnes (MT) of municipal solid waste (MSW) yearly by 2031, rising by another 436 MT by 2050. By 2031 alone, this increasing garbage will need almost 23.5×10^7 m^3 of landfill space, equivalent to 1175 hectares of land every year. Assuming a landfill height of 20 m, the total land required for disposal between 2031 and 2050 is projected to be 43,000 hectares if this trend continues. These estimates are predicted on a 0.45 kg/day per capita garbage production. Gasification technology stands out among the most effective and clean ways to solve the growing waste problem in an environmentally responsible way. A thermochemical process called gasification turns solid waste into syngas at high temperatures, usually about 600 °C, producing up to 1000 kWh of power from one tonne of MSW. The precise choice of operating temperature in a thermochemical conversion process depends on several critical factors, including the type of reactor used, the characteristics of the waste material, and the thermal behavior of the resulting ash. Different reactor configurations such as fixed-bed, fluidized-bed, and entrained-flow systems have distinct heat transfer patterns, residence time profiles, and flow dynamics, all of which affect the required temperature for efficient operation [5]. The nature of the waste, including moisture content, ash content, and proportions of cellulose, hemicellulose, and lignin, influences how the material responds to heat and the extent of volatile release during decomposition [6]. Feedstocks with high moisture require more energy input, which may reduce effective reaction temperatures, while high lignin or ash content may alter decomposition behavior [7]. The ash softening and melting points hold particular importance, as operation above these temperatures can cause slag formation, bed agglomeration, or equipment fouling [8]. Maintaining the operating temperature below the ash deformation point remains essential to ensure process stability and equipment longevity [9]. These factors together define a safe and optimal temperature range that balances reaction efficiency, syngas quality, and operational reliability. Solid waste gasification comprises several sequential phases combining endothermic and exothermic reactions [10,11].

Beginning at temperatures up to 160 °C, heating and drying combine physical and chemical processes. Drying is a complex process characterized by moisture evaporation. Releasing a major amount of volatile chemicals from carbonaceous fuel, pyrolysis is a vital and limiting stage. As schematically illustrated in Figure 1, the volatile compounds released during pyrolysis significantly contribute to the composition of the product gas in the subsequent gasification process. These volatiles create an environment rich in fuel gases that are readily ignitable around solid waste. The chemical makeup and structural properties of the waste primarily influence the nature, quantity, and characteristics of the chemical species generated during pyrolysis [12]. Additionally, factors such as temperature, pressure, the surrounding atmosphere, the composition of the waste, and the heating rate imposed by the specific reactor design play crucial roles in determining the outcomes of the pyrolysis process [13]. Because devolatilization releases a large variety of chemical components, it is essential to keep in mind that many of these components require hydrogen to form molecular bonds. Consequently, the process of devolatilization results in the depletion of hydrogen from the carbonaceous matrix that was present in the waste in the initial stages.

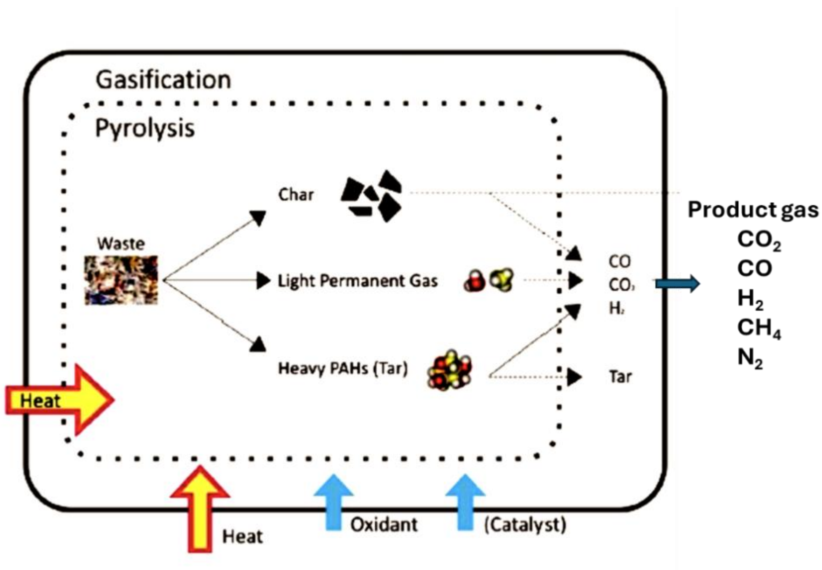

Figure 1. Schematic representation of Municipal Solid Waste to pyrolysis and gasification stages.

Numerous studies and performance evaluations have demonstrated that thermochemical conversion technologies play a vital role in integrated municipal solid waste (MSW) management systems [14–17]. These technologies form the backbone of many successful waste management operations implemented globally. Waste-to-energy (WtE) systems based on gasification can function as standalone solutions or be incorporated into integrated or modular frameworks that combine pyrolysis, gasification, and combustion processes [18].

These systems are often categorized into three principal components: producer gas generation, producer gas usage, and gas purification. The producer gas generation section ascertains the kind and composition of syngas produced, contingent upon the properties of the solid waste and the gasification process employed. The producer gas usage section examines the appropriateness of syngas for various energy conversion devices—such as steam turbines, gas engines, or gas turbines—affected by characteristics including syngas temperature, heating value, and purity. This transitions to the third section, gas cleaning, which guarantees the elimination of contaminants such tar, dust, alkali metals, and other inorganic impurities to satisfy the operating standards of energy conversion apparatus. Over the past two decades, a wide range of gasification technologies have been developed [19–21]. Operating at lower equivalence ratios often results in incomplete char conversion and higher tar formation.

Although higher equivalence ratio (ER) values promote the oxidation of a portion of the syngas, which reduces its calorific value, they may also result in partial combustion within the downstream combustion chamber [22–25]. The most important differences among gasification technologies are determined by several fundamental factors, including the method of heat supply, whether it is direct or indirect; the operating pressure, where above-atmospheric pressure allows for increased throughput, higher hydrogen production, and smaller gas clean-up systems; and the operating temperature range, which influences the characteristics of bottom ash, often producing molten or vitreous slag that is easier to handle and dispose of. Even though high-pressure systems have performance advantages, they need much greater investment and operational expenses, which can make them unfeasible for waste-to-energy (WtE) applications. The feed mechanism, which is normally positioned at the top and moved by gravity, air flow, or mechanical methods, and the selection of the oxidant (air, oxygen, or oxygen-enriched air) are two more distinctions. Steam is primarily utilized for the gasification of coal or biomass. Through the utilization of the thermal gasifier designs, most of the technologies that are currently available for commercial use are designed to generate both heat and electricity from syngas. A small number of them, mainly in Japan, are equipped with a 'power gasifier' configuration or are specifically designed for the manufacturing of chemicals, most notably ammonia [26,27]. This study evaluates the feasibility of gasification as an environmentally sustainable method for managing municipal solid waste (MSW) by co-gasifying MSW with woody biomass in varying proportions, with a fixed air flow rate used as the primary performance measure. The energy efficiency of gasification shows clear differences between municipal solid waste (MSW) and woody biomass due to the composition and properties of the feedstocks. MSW contains a mixture of organic and inorganic materials, which causes variability in gas composition, higher moisture levels, and contaminants that reduce gasification efficiency. In contrast, woody biomass offers more uniform composition, with consistent cellulose, hemicellulose, and lignin content, resulting in cleaner syngas with higher hydrogen and carbon monoxide levels and energy efficiencies between 65 and 75%. MSW gasifiers, although effective at reducing waste volume and managing environmental concerns, often provide lower energy efficiencies, around 50 to 65%, due to feedstock variability and issues such as increased tar formation. Co-gasification of MSW with woody biomass provides a promising method to improve gas quality and energy recovery by balancing the feedstock properties. The biomass component stabilizes gasification reactions, reduces tar content, and increases the calorific value of syngas. This study uniquely evaluates co-gasification performance with varying proportions of MSW and woody biomass under a fixed air flow rate, focusing on how different ratios affect tar reduction, hydrogen and carbon monoxide yields, and thermal stability in a single reactor design. The co-gasification process achieves an energy efficiency near 85%, which surpasses that of individual feedstock gasification and demonstrates enhanced conversion performance.

The novelty of this work lies in the systematic analysis of co-gasification under controlled operational parameters that balance feedstock heterogeneity, revealing optimal conditions for maximum energy recovery and gas quality. By addressing parameters such as temperature control and ash behavior, this study provides essential insights to optimize gasification for heterogeneous feedstocks. The results show that co-gasification improves energy efficiency and syngas quality, offering a sustainable and scalable solution for urban waste management. This research significantly contributes to the advancement of integrated waste-to-energy technologies, supporting environmental protection and circular economic goals.

Notably, this study proposes a technically and economically feasible MSW gasifier model optimized for urban implementation, particularly suited for large metropolitan areas such as Delhi and Chennai, each spanning over 750 km^2. These cities generate substantial MSW volumes, and deploying gasification units could significantly improve waste management and generate clean energy on a large scale. The design leverages the co-gasification of MSW with readily available woody biomass, such as construction timber and horticultural debris, which are abundant in regions of Tamil Nadu, especially in the northern and southern districts. These materials are collected through local waste collection networks serving construction and landscaping activities.

In industrial zones such as the northern and western districts of Hyderabad, factories and institutional kitchens generate substantial quantities of food waste, which can serve as an additional feedstock for localized gasification plants. The produced syngas can be utilized for thermal or electrical energy generation to power on-site operations, while the char/ash residue can be repurposed in nearby cement plants, thereby closing the loop in a circular economy model. This integrated approach demonstrates the viability of gasification as a practical, scalable, and environmentally sustainable solution for urban MSW management in India.

2. Materials and Methods

2.1. Pre-Treatment and Sorting Processes for Municipal Solid Waste (MSW)

The collection of municipal solid waste (MSW) took place across several districts in the Indian state of Tamil Nadu. A variety of inorganic materials, including paper, cardboard, plastics, textiles, rubber, leather, and wood, are commonly found in landfill waste. To determine the typical composition of the initial waste samples, these materials were sorted into four distinct categories. Type A includes paper and cardboard, which are often recyclable. Type B consists of plastics, a challenging material to manage due to its variety and resistance to biodegradation. Type C is made up of textile and rubber waste, both of which require specialized recycling processes. Finally, Type D contains wood waste and other inorganic elements, such as metals, which can be recycled or repurposed for different uses. This classification helps provide a clearer understanding of the waste composition and informs better waste management strategies. Since plastics typically surpassed the maximum permissible size of 4 cm for gasification and frequently created clogs in both the feeding system and the gasifier, they were completely removed from the feedstock. The remaining categories were each sampled at a weight of 75–80 kg and then sun-dried for a period of twenty-four hours before being gasified. The moisture level and dry mass of the material were determined by calculating the weight difference between the initial and final weights resulting from a fourteen-day drying interval.

2.2. Proximate and Ultimate Analysis

The feedstock used in this study was a combination of tamarind wood chips and municipal solid waste (MSW), both sourced and processed to meet the requirements for gasification experiments. The tamarind wood chips were specifically obtained from Tamil Nadu, India, a region known for its diverse agricultural practices, and they were selected for their suitability as a biomass source. The chips were measured to have an average size of approximately 10 cm in length and 6 cm in diameter, indicating a typical woody biomass structure that would be compatible with the gasification process. In addition to the wood chips, the feedstock included MSW, which was characterized by a more variable composition and particle size. The MSW was pre-processed to achieve a particle size range between 0.6 cm and 4 cm, ensuring that the material would be appropriately sized for the gasifier's operation. The particle size of MSW is important because it affects the material's residence time in the reactor, its exposure to heat and air, and consequently its overall conversion efficiency during the thermochemical processes of drying, pyrolysis, and gasification. By using both tamarind wood chips and MSW, the study aimed to explore the potential for co-gasification, where biomass and waste materials are converted into valuable energy products such as syngas. The combination of wood and MSW in different proportions offers a unique opportunity to evaluate the effects of different feedstock compositions on the performance of the gasification process, particularly in terms of gas composition, tar production, and overall system efficiency. Given the high initial moisture content of the MSW, which ranged from 60% to 70%, the material underwent pre-drying to reduce its moisture content to the maximum allowable limit of 35%. This moisture reduction was necessary to ensure stable operation in the transient-state gasifier, as described in Section 2.3. To determine the proximate composition of the feedstock, including moisture, volatile matter, fixed carbon, and ash content, a thermogravimetric analysis (TGA) was conducted using a thermal analyzer. The results of the proximate and ultimate analysis for the MSW feedstock are provided in Table 1.

Table 1. Proximate and ultimate analysis of MSW.

Proximate Analysis		Ultimate Analysis	
Moisture	5.33%	Moisture	5.33%
Volatile Matter	86.75%	Carbon	57.45%
Ash	3.10%	Hydrogen	7.70%
Fixed Carbon	4.82%	Oxygen	24.96%

2.3. Downdraft Gasifier Design

The downdraft gasifier used in this study has a rectangular configuration and operates with a mixture of municipal solid waste (MSW) and woody biomass. This arrangement is recognized for generating less tar while effectively enabling ash removal. As the feedstock moves downward through the gasifier, moisture is eliminated in the drying zone prior to entering the pyrolysis zone, where it undergoes thermochemical decomposition into char, tars, and gases. Certain unconverted substances experience combustion. In the next oxidation zone, tars undergo thermal cracking at high temperatures and oxidation, yielding comparatively clean product gas. This gasifier necessitates feedstock preconditioning to lower moisture content to acceptable levels. The system is designed to handle materials with high bulk density, meaning it can efficiently process dense, compact materials. It operates in a stratified downdraft mode, where the materials are subjected to a downward flow of gases. This mode allows heavier particles to settle at the bottom, while lighter particles are carried upwards, facilitating more efficient processing. Operating just above atmospheric pressure improves the system's efficiency by enhancing the conversion process. This configuration makes it particularly suitable for applications like thermal flare burners, which are used to burn off excess gases in various industrial operations. The system's design ensures stable and effective operation, even with materials that have a high density. Figure 2 depicts the design and operation of the system. The gasification zone is sustained at temperatures of 1200 °C or above to guarantee effective tar reduction. This gasifier design is appropriate for fuels with elevated bulk densities, such as wood and municipal solid waste (MSW), which in this investigation exhibited bulk densities of around 1000 kg/m^3 and 800 kg/m^3, respectively.

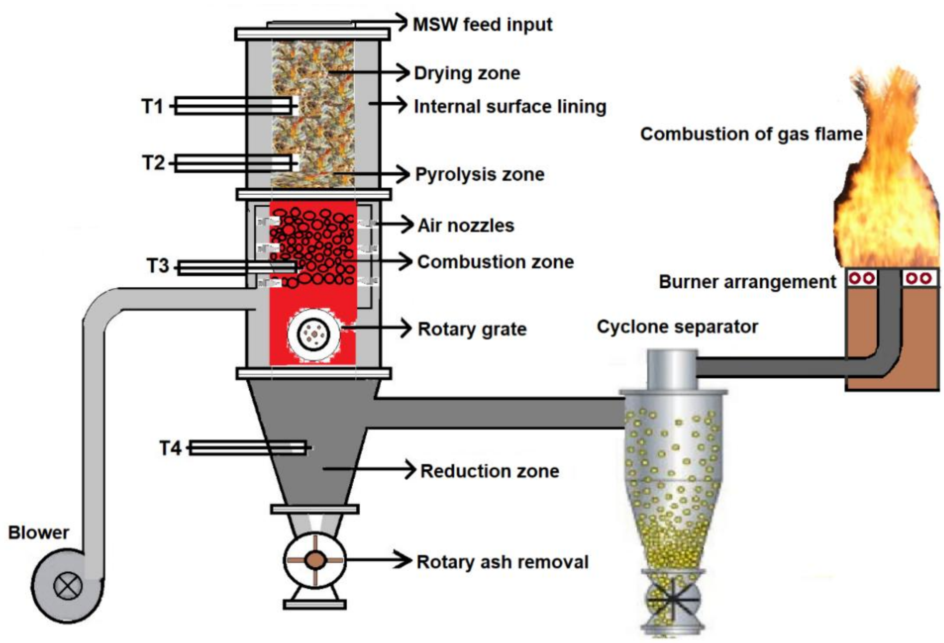

Figure 2. Schematic diagram of MSW stratified down draft gasifier.

The gasifier runs at sub-atmospheric pressure, specifically below 30 cm of the water column. The spinning grate mechanism and the centrally located air nozzle duct are two key design elements that help it run efficiently. The strategic design of these components maximizes the efficiency of the gasification process. The rotary grate is designed to reduce char ash formation, thus immediately enhancing overall gasification efficiency. The entire system is also well insulated, minimizing heat loss and enhancing performance, thus maximizing thermal efficiency. Particularly for the purpose of converting solid waste, the architecture is tuned to be able to tolerate reactions that take place within the gasification zone at extremely high temperatures. A comprehensive set of technical calculations serves as the foundation for this design technique. Figure 3 depicts a pilot-scale model of Yes the gasifier, which demonstrates the features of the producer gas flame at two different periods of operation: the first hour of operation and the eighth hour of operation.

Preliminary phase at the first hour — Final phase at the eighth hour

Figure 3. Producer gas flame from MSW gasification utilized at various operational stages.

2.4. Synergistic Gasification of Woody Biomass and Municipal Solid Waste

The feedstock was categorized into five distinct groups based on the weight proportions of wood waste and municipal solid waste (MSW) to examine their impact on the gasification process. These categories included 100% wood waste, a 75% wood waste and 25% MSW mixture, a 50:50 mix of wood waste and MSW, a 25% wood waste and 75% MSW mixture, and 100% MSW. The feedstock for each group was introduced into the gasifier at a consistent input rate of 9 kg/h, ensuring uniformity across all experimental runs. This method allowed for the systematic evaluation of how different ratios of wood waste and MSW affected key parameters such as gas quality, tar formation, and gas flow rate, providing insights into the potential for optimizing feedstock composition in the gasification process. To initiate the process, the reactor initially operated in suction mode to preheat the charcoal bed, facilitating ignition. Once stable combustion was achieved, the system switched to pressure mode for sustained operation. Within the reactor, the feedstock underwent sequential thermochemical transformations, drying, pyrolysis, gasification, and reduction each occurring in dedicated zones. The average residence time for each type of feedstock in the reactor was approximately one hour. Eight Type K thermocouples spread around the reactor bed captured temperature data. An orifice meter combined with a differential manometer was used to track air and gas flow rates. Averaged over five experimental runs, the data were shown in Table 2. This operational approach is especially appropriate for poorer nations, where labor costs are low and batch processes are financially feasible. Trial 3 demonstrated superior performance among the examined combinations, exhibiting elevated internal gasifier temperatures relative to the other trials, as elaborated in the subsequent sections.

Table 2. Operation parameters of the MSW down draft gasifier system.

Sl. No.	Particulars	Total Average Values						
		Total	Gasifier Zone Temperature °C				Air Flow	Gas Flow
		Operating Hours	Combustion T 4	Reduction T 3	Pyrolysis T 2	Drying T 1	Rate m^3/h	Rate m^3/h
1	Run 1 100% Wood	8:18	871.95	744.53	641.8	514.26	15	35
2	Run 2 75% Wood + 25% MSW	8:32	847.05	723.64	563.4	463.28	15	33
3	Run 3 50% Wood + 50%MSW	8:16	883.57	757.1	659.14	558.88	15	38
4	Run 4 25% Wood + 75%MSW	8:29	724.79	657.10	486.26	439.28	15	30
5	Run5 100% MSW	8:19	717.11	601.79	397.6	331.94	15	25

3. Mass and Energy Balance of MSW and Wood Waste

The mass balance of the entire system was determined by utilizing a constant air flow rate of 15 cubic meters per hour throughout the evaluation process. During the course of the experiment that lasted for 8.16 h, a total of 30 kg of municipal solid trash and wood waste were processed. Taking into consideration the amount of ash that is present in the municipal solid trash, this is equivalent to an average conversion rate of around 3.5 kg per hour. The flow rate of producer gas was measured to be 38 kg per hour on average. Several different causes are responsible for the disparity that exists between the anticipated and measured flow rates of producer gas. When it comes to the precision of the measurements made by the gas flow devices, there is a possibility of variations. Table 3 provides the input characterization of Municipal Solid Waste (MSW) and the corresponding producer gas composition.

Table 3. Input Characterization of Municipal Solid Waste (MSW) and Output Composition of Producer Gas.

Input	**Output**
MSW Analysis % Wet Basis	**Producer Gas Analysis in %**
C = 38.65	CO = 14
H = 6.24	H_2 = 15
O = 40.53	CH_4 = 2.5
N = 1.25	H_2O = 7.5
S = 0.23	CO_2 = 12
Cl = 0.60	N_2 = 48.7
Ash = 12.50	O_2 = 0.3
H_2O = 24.91	

Feed input:

$$\dot{m}_{C,fuel} = \dot{m}_{fuel} \cdot w_C \tag{1}$$

$$\dot{m}_{Hydrogen} = \dot{m}_{fuel} \cdot \left(w_H + \frac{2}{18} \cdot w_{moisture} \right) \tag{2}$$

$$\dot{m}_{Oxygen} = \dot{m}_{fuel} \cdot \left(w_O + \frac{16}{18} \cdot w_{moisture} \right) \tag{3}$$

Input air:

$$\dot{n}_{H,air} = \frac{2y_{H_2} \cdot Q_{air}}{22.4} \tag{4}$$

$$\dot{n}_{N,air} = \frac{2y_{N_2} \cdot Q_{air}}{22.4} \tag{5}$$

$$\dot{n}_{O,air} = \frac{\left(2y_{O_2} + y_{H_2}\right) \cdot Q_{air}}{22.4} \tag{6}$$

Output producer gas:

$$\dot{n}_{C,gas} = \frac{\left(y_{CO} + y_{CO_2} + y_{CH_4}\right) \cdot Q_{gas}}{22.4} \tag{7}$$

$$\dot{n}_{H,gas} = \frac{\left(2y_{H_2} + 2y_{H_2O} + 4y_{CH_4}\right) \cdot Q_{gas}}{22.4} \tag{8}$$

$$\dot{n}_{O,gas} = \frac{\left(y_{CO} + 2y_{CO_2} + y_{H_2O}\right) \cdot Q_{gas}}{22.4} \tag{9}$$

$$\dot{n}_{N,gas} = \frac{2y_{N_2} \cdot Q_{gas}}{22.4} \tag{10}$$

$$P_{in} = \dot{m}_{fuel} \cdot HHV_{fuel} \quad \left(MJ\ hr^{-1}\right) \tag{11}$$

4. Results and Discussion

4.1. Gasifier Performance

The instantaneous performance data, which includes the gas yield and heating value, are presented in Table 4 for each of the respective runs of the gasifier while it is in operation. The highest gas production was observed during Trial 3, which utilized a feedstock blend of 50 percent wood and 50 percent municipal solid waste. This trial achieved a peak gas flow rate of 38 m^3/h, with the corresponding maximum energy content of the producer gas reaching 1250 kcal/Nm^3. Throughout all five trials, the air flow rate was consistently maintained at 15 m^3/h. However, in Trials 1 and 3, the process moves toward flame pyrolysis and peak gasification as more charcoal is gasified. This indicates that the process is progressing. Because higher pyrolysis temperatures result in larger pyrolysis reaction rates, they make it possible to increase the consumption of both wood and municipal solid waste. The capacity of this gasifier design to produce less tar is one of its most notable characteristics. This is accomplished by delivering a more consistent mixture of fuel and air through three rows of nozzles that are arranged in contrast to one another. It has been found that to achieve optimal performance, it is necessary to distribute wood, municipal solid waste, and air in a manner that is uniform both spatially and temporally.

Table 4. Performance results of the downdraft gasifier under various feedstock blends.

Key Values	**MSW Downdraft Gasifier**				
	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**
Composition of MSW	**100% Wood**	**75% Wood + 25% MSW**	**50% Wood + 50% MSW**	**25% Wood + 75% MSW**	**100% MSW**
Moisture content of (%)	5.33	20	5.33	25	25
Flow rate of air (m^3/h)	15	15	15	15	15
Equivalence ratio	0.3	0.5	0.4	0.3	0.35
Flow rate of gas (m^3/h)	35	33	38	30	25
Particulate (g)	0.5	0.3	0.2	0.5	0.4
Tar (%)	0.3	1.2	1.3	1	2
CO (%)	12	14	15	14	11
H_2 (%)	14	11	16	14.8	12
CH_4 (%)	3.5	3.2	3	3.4	6
CO_2 (%)	12	15	11.2	11.5	13
H_2O	9.5	7.4	6.1	6.8	7
N_2 (%)	48.8	49	48.5	48.7	50
O_2	0.2	0.4	0.2	0.8	1

4.2. Tar Concentration

Figure 4 shows the variation in tar concentrations and bed temperatures during different runs in the gasifier. Tar concentrations ranged from 0.3% to 2%, indicating fluctuations in the efficiency of the gasification process. Lower tar concentrations suggest more complete gasification, while higher concentrations indicate incomplete breakdown of volatile compounds. The temperature in the combustion zone reached 883 °C, which is ideal for the partial combustion of feedstock and providing heat for gasification, while the drying zone had a lower temperature of 331 °C, necessary for removing moisture from the feedstock before it enters the higher-temperature zones. These temperature variations are critical for optimizing the drying, pyrolysis, and gasification processes, influencing both tar formation and overall system efficiency. Temperature oscillations were noted in all areas of the bed during the studies, apart from the reactor's bottom. The principal factor contributing to this fluctuation is the intermittent activation of the feeding system. As the gasification process progressed and the municipal solid waste (MSW) level in the gasifier decreased, the addition of wood debris and MSW at the upper part of the bed led to a downward displacement of the bed. This displacement caused a significant shift throughout the bed, altering the temperature distribution. Figure 4 demonstrates that during Run 3, which involved 30 kg of wood waste combined with 30 kg of MSW, the system maintained optimal tar levels throughout the eight-hour continuous operation of a single fixed-bed batch. This performance in Run 3 was more favorable compared to the other experimental runs, highlighting the efficient balance between wood and MSW that contributed to better tar reduction and overall gasification efficiency.

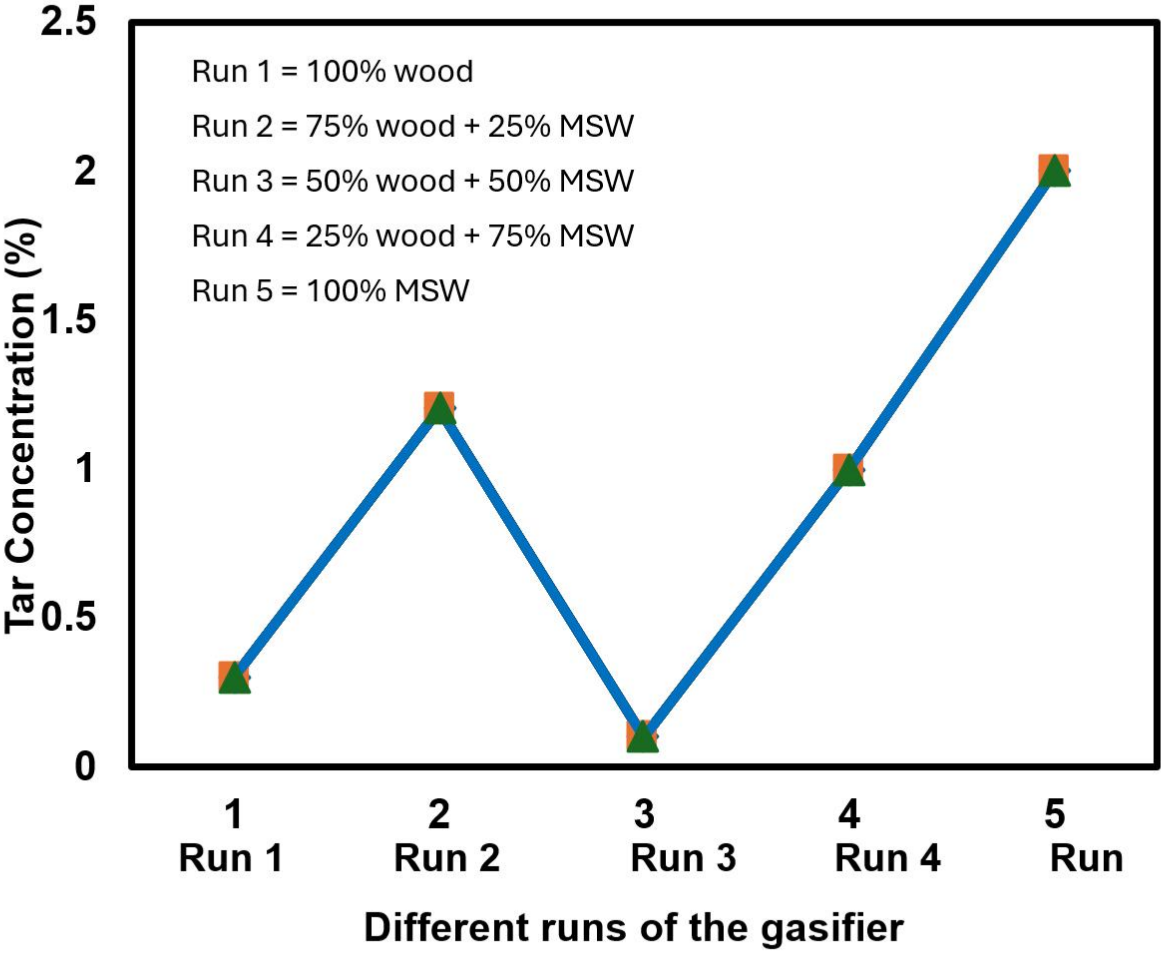

Figure 4. Tar yield profile under different operational runs.

4.3. Mass and Energy Balance

The energy input for the gasification process is calculated by multiplying the fuel consumption rate by the heat of combustion on an as-received basis. Given that the heat of combustion on a dry basis is 14.8 MJ/kg, and considering the moisture content of 24.91%, the heat of combustion on an as-received basis is 14.25 MJ/kg. With a fuel consumption rate of 30 kg/h, the energy input is calculated as 30 kg/h × 14.25 MJ/kg, resulting in an energy input of 427.5 MJ/h.

$$P_{in} = 30 \cdot 14.5 = 435\ MJ\ hr^{-1} \quad (12)$$

The chemical energy in the producer gas is calculated by considering the molar flow rates of the combustible components in the gas and multiplying them by their respective higher heating values (HHV, in MJ/Nm^3). HHV represents the energy content of a unit volume of gas, and by determining the flow rates of key combustibles such as hydrogen, carbon monoxide, methane, and other volatile compounds, the total chemical energy can be derived. This calculation helps in evaluating the energy output of the producer gas and assessing the efficiency of the gasification process.

$$P_{out,chemical} = \sum_i \dot{n}_i \cdot HHV_i = \frac{Q_{gas}}{22.4} \cdot \sum_i y_i \cdot HHV_i \quad \left(MJ\ hr^{-1}\right) \quad (13)$$

$$P_{out,chemical} = \frac{75}{22.4} \cdot \left(0.14 \cdot 283.0 + 0.15 \cdot 285.8 + 0.025 \cdot 890.4\right) = 350\ MJ\ hr^{-1} \quad (14)$$

Then the equation for the sensible heat becomes:

$$P_{gas.sensible} = \frac{v_{gas}}{22.4}.C_p\left(T_{gasout} - T_{ambient}\right)(MJ\ hr^{-1}) \tag{15}$$

Additionally, it is necessary to consider the heat that is lost to the environment in addition to the sensible heat that is transported by the producing gas. However, the exterior surface of the gasifier is not insulated, which results in an estimated loss of heat of roughly 10 MJ/h due to convection and radiation. The gasifier is coated with high-alumina refractory cement on the inside. With the information that has been provided, it is now possible to compute the total amount of energy that is being expelled from the system.

$$P_{out} = P_{out,\ chem} + P_{out,\ s} + P_l = 350 + 77 + 10 = 435\ MJ\ hr^{-1} \tag{16}$$

Comparing Equations (12) and (16)

$P_{in} = 437 MJ\ hr^{-1}$ $\qquad$ $P_{out} = 435\ MJ\ hr^{-1}$

The validity of the energy input-output assessment for the gasifier system is confirmed by the observed results, which show a significant agreement between the projected and actual heat and mass balance. This assessment indicated that the amount of fuel input closely aligned with the amount of oil produced, demonstrating that the system operates efficiently in terms of both energy and mass conversion. The examination of the mass and energy balance highlighted this close match, validating the accuracy of the energy input calculations and the system's overall performance in converting feedstock into useful products.

It is important to consider that gas samples were collected several hours into the run, which means that the composition of the residual fuel in the reactor may have changed over time. As the gasification process progresses, the fuel undergoes thermochemical transformations, and the distribution of volatile compounds, char, and gas may shift. This change in fuel composition could influence the gas composition and the overall performance of the system, potentially affecting the accuracy of the gas samples taken later in the process. Therefore, the timing of sample collection is crucial in ensuring the reliability of the data and the interpretation of the system's behavior. Although it is anticipated that drying took place at an early stage, it is also possible that the composition of the dry feedstock was altered because of extended heating. The mass and energy balance were carried out at a rate of 45 cubic meters per hour, which was optimal for air movement. It is noteworthy that the gasification process was able to attain an estimated efficiency of 98% under these conditions, which demonstrates the efficacy of the system in turning municipal solid waste into syngas.

4.4. Comparison with Experimental Results

The performance outcomes of the fabricated gasifier were compared with empirical data from prior investigations concerning woody biomass and municipal solid waste [28,29]. The findings predominantly align with the existing literature, as illustrated in Table 5. This unequivocally illustrates that the downdraft MSW gasifier created in this study is both technically robust and appropriate for practical use.

Table 5. Experimental data compared with other results.

Operating Parameters	Experimental Data		
	Saravanakumar et al. [29]	**Shweta T and Somnath N [28]**	**Present Work**
Feedstock	Wood	MSW	MSW + Wood
Running hours	5	4	8
Feed rate kg h^{-1}	10	6	9.38
Air flow rate m^3h^{-1}	29	35	15
Gas flow rate m^3h^{-1}	25	12.45	38
Total fuel consumed kg	65	24	90.50

4.5. Technology Implementation

The proposed MSW gasifier model could be well-suited for implementation in metropolitan areas such as Delhi and Chennai, which cover large urban regions of approximately 750 km^2 each. These cities, with their significant population and substantial amounts of municipal solid waste (MSW), could greatly benefit from the efficient waste-to-energy solutions offered by the gasifier model. By converting MSW into energy, the system could help address waste management challenges while simultaneously generating clean energy, making it a viable option for large-scale urban waste management and energy production in these densely populated cities.

Construction timber and horticultural debris are readily accessible via wood waste collectors, especially prevalent in the northern and southern districts of Tamil Nadu. These collectors generally provide garbage disposal services for building and landscaping sites. The industrial areas in the northern and western regions of Hyderabad contain numerous factories and canteens, generating a steady supply of food waste. Establishing gasification facilities in these places would enhance localized waste management and energy recovery. The produced gas can function as a thermal or electrical energy source for the facility, while the char ash byproduct may be employed in adjacent cement facilities, so supporting a circular economy model.

5. Conclusions

This study examines the co-gasification of municipal solid waste (MSW) and woody biomass in varying ratios to evaluate tar content, syngas composition, and the volumetric flow rate of the generated gas. Because of the lightweight and heterogeneous character of the waste, the fixed-bed stratified downdraft gasifier was able to work effectively up to a maximum of forty percent municipal solid waste content. After that point, bridging in the hopper occurred. An increase in the proportion of municipal solid waste (MSW) in the feedstock improved the quality of the producer gas, particularly by raising the concentrations of CO and H_2O. The highest gas flow rate of 38 Nm^3/h. was achieved with a 50:50 (*w*/*w*) mixture of wood waste and municipal solid waste, indicating optimal performance under these conditions. These results suggest that gasification serves as a promising, environmentally friendly technology for the value of municipal solid waste, offering a sustainable approach to energy recovery through the production of cleaner producer gas. This study presented a modified stratified downdraft gasifier design as a means of overcoming the various problems that are typically connected with traditional downdraft fixed-bed gasifiers, particularly those that involve high tar content. The unique configuration, which consisted of three rows of air nozzles that were opposite one another, made it possible to mix the feedstock and air in a regular manner, which led to a significant reduction in the development of tar. A demonstration of the reactor's thermal stability and operational reliability was carried out over the course of eight hours of continuous operation. The usefulness of this design for decentralized waste-to-energy applications is highlighted by the enhanced gas quality as well as the overall efficiency. As an additional point of interest, the mass and energy balance calculations demonstrated a high gasification efficiency when municipal solid waste was utilized, hence verifying the system's potential for practical implementation in urban and industrial settings.

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Nomenclatures

P_{in}	Power intake (MJ/h)
Q_{gas}	Gas throughput rate (m^3/h)
$\dot{m}_{fuel}$	Rate of fuel consumption (kg/h)
HHV_{fuel}	Heat content of fuel (MJ/kg)
$P_{out,chem}$	Energy output from chemical reactions (MJ/h)
$\dot{n}_i$	Molar transfer rate *i* (kmol/h)
y_i	Relative amount of component *i* (m^3 m^{-3})
$c_{p,i}$	Specific heat of the substance *i* (kJ/kmol·K)
σ	Stefan Boltzmann constant (W/m^2·K^4)
ε	Radiative heat emission factor
A	External surface area of the gasifier (m^2)
$T_{gas\ out}$	Temperature of the gas leaving the system (K)
$T_{ambient}$	Temperature of the surroundings (K)
$P_{out,sensible}$	Sensible thermal energy (MJ h^{-1})

K	Reaction equilibrium factor
T_{eq}	Thermal balance temperature (K)
A_i … E_i	Heat capacity function coefficients for the species *i*
p_{CO2}	CO_2 component pressure (Pa)
p_{H2}	H_2 component pressure H_2 (Pa)
p_{CO}	CO component pressure CO (Pa)

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