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Research Article

Production of Hydrogen-Rich Syngas from Mixed Wastes via Gasification Process

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Abstract: This study investigates the relationship between cold gas efficiency and the H_2/CO ratio in the gasification of various biomass-based waste streams, aiming to optimize the energy and chemical performance of the produced syngas. Experiments were conducted using green waste, olive pomace, and sewage sludge under varying operational conditions, including different temperatures, gasifying agents, and flow rates. The calorific value of the resulting syngas ranged between 5 and 14 MJ/kg, while gas conversion efficiencies varied from 28% to 68%. Maximum syngas quality was achieved at higher temperatures and lower gasifying agent flow rates.The H_2/CO ratio reached up to 5 for green waste, 4 for olive pomace, and 6 for sewage sludge, indicating the potential to produce hydrogen-rich syngas from diverse feedstocks. Cold gas efficiencies were recorded as 92%, 62%, and 73%, respectively. These results demonstrate that waste-specific operational optimization can significantly enhance syngas composition and efficiency. This research contributes to the waste-to-energy literature by providing a comparative assessment of mixed waste gasification under different conditions, with a focus on hydrogen-rich syngas production. The innovative aspect lies in the integrated evaluation of both energy efficiency and H_2/CO balance across multiple feedstocks. The syngas produced can be utilized directly in energy systems such as gas turbines and internal combustion engines or serve as an intermediate for chemical synthesis processes, including methanol and ammonia production. The findings offer a promising approach for sustainable waste management and resource recovery through thermochemical conversion.

Keywords: *Gasification, Hydrogen, Syngas, Sustainable waste management, Waste-to-energy.*

Gazlaştırma Prosesi ile Karma Atıklardan Hidrojence Zengin Sentez Gazı Üretimi

Öz. Bu çalışma, çeşitli biyokütle temelli atık akışlarının gazlaştırılması sürecinde soğuk gaz verimliliği ile H_2/CO oranı arasındaki ilişkiyi incelemekte olup, üretilen sentez gazın enerji ve kimyasal performansının optimize edilmesini amaçlamaktadır. Deneyler; yeşil atık, zeytin posası ve arıtma çamuru kullanılarak farklı sıcaklıklar, gazlaştırıcı ajan türleri ve debi koşulları altında gerçekleştirilmiştir. Elde edilen sentez gazın ısıl değeri 5–14 MJ/kg arasında değişirken, gaz dönüşüm verimi %28 ila %68 arasında bulunmuştur. En yüksek sentez gaz kalitesi yüksek sıcaklık ve düşük gazlaştırıcı debisinde elde edilmiştir. H_2/CO oranı yeşil atık için 5'e, zeytin posası için 4'e ve arıtma çamuru için 6'ya kadar ulaşmıştır; bu durum farklı atık türlerinden hidrojen açısından zengin sentez gazı üretilebildiğini göstermektedir. Soğuk gaz verimliliği sırasıyla yeşil atıkta %92, zeytin posasında %62 ve arıtma çamurunda %73 olarak kaydedilmiştir. Bu sonuçlar, atığa özgü işletim optimizasyonlarının sentez gaz kompozisyonunu ve verimliliğini önemli ölçüde

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iyileştirebileceğini ortaya koymaktadır. Bu araştırma, farklı işletme koşulları altında karışık atıkların gazlaştırılması konusunda karşılaştırmalı bir değerlendirme sunarak atıktan enerji üretimi literatürüne katkı sağlamaktadır. Çalışmanın yenilikçi yönü, çoklu atık türlerinde enerji verimliliği ile H_2/CO dengesinin birlikte değerlendirilmesidir. Üretilen sentez gaz; gaz türbinleri ve içten yanmalı motorlar gibi enerji sistemlerinde doğrudan kullanılabileceği gibi, metanol ve amonyak gibi kimyasal sentez süreçlerinde ara ürün olarak da değerlendirilebilir. Bulgular, sürdürülebilir atık yönetimi ve kaynak geri kazanımı açısından umut verici bir yaklaşım sunmaktadır.

Anahtar kelimeler: *Atıktan enerji, Gazlaştırma, Hidrojen, Sentez Gaz, Sürdürülebilir atık yönetimi.*

1. Introduction

Meeting the growing energy demand in a sustainable manner, reducing environmental impacts, and addressing waste management challenges are among the primary priorities of contemporary energy policies. In this context, biomass- and waste-based energy production technologies, considered as alternatives to fossil resources, hold strategic importance for both environmental sustainability and energy security. Gasification, one of the thermochemical conversion processes, is an effective method that converts solid or liquid carbon-based feedstocks into synthesis gas (syngas) at high temperatures in a limited oxygen or steam environment [1]. The resulting syngas is composed of hydrogen (H_2), carbon monoxide (CO), methane (CH_4), and carbon dioxide (CO_2), and can be utilized directly for energy production or as an intermediate for chemical synthesis[2].

The efficiency of the gasification process is assessed through various performance indicators. One of the most widely used metrics is cold gas efficiency (CGE), which indicates the extent to which the chemical energy of the fuel is converted into syngas [2]. On the other hand, the quality of syngas is directly related to the proportions of hydrogen and carbon monoxide, particularly the H_2/CO ratio. This ratio serves as a critical indicator for applications such as Fischer-Tropsch synthesis, methanol production, and hydrogen enrichment [3,4]. Therefore, both CGE and the H_2/CO ratio are fundamental parameters that should be jointly considered in evaluating the thermodynamic and practical feasibility of gasification systems [5].

Numerous studies on gasification technologies have demonstrated the significant influence of process parameters on syngas composition, energy conversion efficiency, and final product quality. In biomass- and solid waste-based systems, factors such as reactor type, operating temperature, steam-to-carbon ratio (S/C), oxygen supply, and in-reactor catalytic activity play a vital role in determining both the H_2/CO ratio and CGE [1,2]. Operating at high temperatures (800–1000°C) reduces the tar and pitch content of gaseous products and enhances the efficiency of pyrolysis and oxidation reactions, promoting the formation of higher proportions of H_2 and CO in the syngas [3]. In steam-assisted gasification processes, significant increases in the H_2/CO ratio have been observed due to the water-gas shift reaction ($CO + H_2O \rightleftharpoons CO_2 + H_2$) [4]. However, a slight decrease in CGE can occur under such conditions due to the associated energy input and carbon losses during the reaction.

When the H_2/CO ratio, an indicator of high-quality syngas, is low, conversion efficiency toward target products also declines [5]. The use of oxygen or air as the gasifying agent typically results in a lower H_2/CO ratio. Biomass feedstocks with low H/C and high O/C ratios also yield syngas with a low H_2/CO ratio [6]. A major limitation in traditional coal gasification systems is the difficulty in producing syngas with the desired H_2/CO ratios. Typically, H_2/CO ratios of approximately 1, 2, and 3 are required for the synthesis of aldehydes, methanol/ethanol, and methane, respectively [7]. Accordingly, examining the effect of the H_2/CO ratio on syngas production performance is of great importance. It has been shown that syngas yield increases with rising H_2/CO ratios, whereas lower ratios reduce the efficiency of synthesis reactions and increase the risk of carbon deposition [8]. Syngas obtained from biomass gasification generally has an H_2/CO ratio close to or below one, depending on the feedstock, reactor type, and operating parameters. The use of catalysts can improve this ratio, and many studies in the literature investigate process conditions and catalytic strategies to enhance H_2/CO ratios [9–13].

Tanoh et al. [14] conducted the gasification of green waste and wood using a two-stage system consisting of a rotary kiln for pyrolysis and a tubular reactor for volatile matter reforming. They reported that the H_2 content in syngas increased from 29% to 50% at 1200°C and reached 54% at 1300°C, with the H_2/CO ratio remaining around 1.4 at both temperatures. Pedrazzi et al. [15] used a pilot-scale downdraft gasifier in an integrated application of landfill gas and biomass gasification using green waste. In their study, the H_2 content and H_2/CO ratio of syngas were found to be 18% and 0.71 by volume, respectively.

Research shows that different types of feedstocks have unique effects on H_2/CO and CGE. For instance, the composition of syngas derived from the gasification of lignocellulosic biomass, refuse-derived fuel (RDF), agricultural residues, and sewage sludge varies depending on moisture content, ash content, and volatile matter content [16,17]. Biomass with a high lignin content is considered more favorable for H_2 production, and increasing the S/C ratio leads to a clear increase in H_2 content while decreasing CO content [18]. Studies focusing on CGE emphasize that efficiency is directly related to gasification temperature, oxidant type (air, pure oxygen, or steam), and reactor configuration. In high-temperature entrained-flow systems, CGE values can exceed 70%, whereas in low-temperature fixed-bed systems, they typically range between 45% and 60% [19,20]. Furthermore, recent catalytic gasification approaches have shown promise for improving both syngas quality and CGE [21].

In conclusion, although there is no direct correlation between H_2/CO ratio and CGE in the gasification process, both parameters must be optimized in conjunction with operating conditions, feedstock properties, and reactor design. Thus, a comprehensive performance evaluation of gasification systems can only be achieved through the integrated analysis of both indicators.

This study systematically investigates the relationship between cold gas efficiency (CGE) and the H_2/CO ratio in the gasification process by considering a range of operating conditions and diverse biomass-derived feedstocks. The findings aim to support the optimization of both the energy and chemical efficiency of syngas production. By quantitatively examining how different waste types simultaneously affect CGE and the H_2/CO ratio, this work contributes to the literature with a detailed insight into waste-specific optimization strategies. Unlike many existing studies that concentrate solely on either syngas composition or energy efficiency, the present study offers a comparative evaluation of both key parameters under consistent experimental conditions, thereby providing a more comprehensive understanding of process performance. The innovative aspect of this research lies in its integrated analysis of hydrogen yield potential and cold gas efficiency across multiple feedstocks, emphasizing the dual utility of gasification for clean energy generation and chemical synthesis, including direct use in power systems and precursor applications such as methanol and ammonia production.

2. Material & Methods

2.1. Assessment of Energy Conversion Efficiency

The syngas produced through gasification is suitable for use in both energy generation and raw material production. Gas fuels can be obtained from biomass gasification to be used in turbines that provide high-efficiency power and heat. The cleaned syngas derived from biomass gasification can be directly combusted in boilers to produce heat and steam with an efficiency of 20–30%, or it can be used for electricity generation in Stirling engines. Literature reports indicate that compressed gasification turbines can achieve electricity generation efficiencies of 40% or higher [22]. Gasification efficiency (η_gas) can be calculated using the equation (1) provided below:

$$\eta = 100 * (HHV_{syngas} * \frac{m_{syngas}}{HHV_{feedstock.}} * m_{feedstock}) \quad (1)$$

HHV_{syngas} can be calculated using (2).

$$HHV_{syngas} = X_{H_2} HHV_{H_2} + X_{CO} HHV_{CO} + X_{CH_4} HHV_{CH_4} \quad (2)$$

m_{syngas} *: weight of the syngas.*

$m_{feedstock.}$*: weight of the feedstock*

HHV_{syngas} *: higher heating value of the syngas*

HHV_i *and* X_i *: represent the higher heating value and mass fraction of the syngas components (i =* H_2*, CO,* CH_4*)*

Channiwala and Parikh [23] developed a unified correlation to estimate the higher heating values (HHV) of fuels based on their elemental compositions. The HHV of the feedstock was calculated using the empirical formula given in Equation (3).

$$HHV\left(\frac{MJ}{kg}\right) = 34.91\,C + 117.83\,H + 10.05\,S - 10.34\,O - 1.51\,N - 2.11\,ash \quad (3)$$

Here, C, H, O, N, and S represent the mass percentages of carbon, hydrogen, oxygen, nitrogen, and sulfur in the feedstock on a dry basis, respectively.

Loha et al. [24] developed an HHV model in terms of MJ/kg of biomass using Aspen Plus, as shown below.

$$HHV\left(\frac{MJ}{kg}\right) = 0.3491\,C + 1.1783 - 0.1034\,O - 0.0151\,N - 0.0211\,ash \quad (4)$$

The efficiency of the gasifier is evaluated through cold gas efficiency and the heating value of the produced syngas. Since cold gas efficiency represents the ratio of the thermal energy content of the syngas to that of the fuel, the heating value of the syngas is a key parameter. Janajreh et al. [25] provided a model for the syngas heating value, as given in the following equation:

$$HHV\left(\frac{MJ}{Nm^3}\right) = 12.63\,C + 12.75\,H + 39.82\,CH_4 + 63.43C_2H_4 \quad (5)$$

The efficiency of the gasification process is evaluated using various parameters such as syngas composition and heating value, cold gas efficiency (CGE), carbon conversion efficiency, and tar content [26,27,28]. Cold gas efficiency is calculated based on the heating values of the produced gas and the feedstock. The equation for calculating cold gas efficiency is provided in Equation (6) [29].

$$\text{Cold gas efficiency } (\eta_{Gas}) = \frac{\text{LHV}_{gas} \times V_{gas}}{\text{LHV}_{biomass} \times \text{m}_{biomass}} \times 100 \quad (6)$$

LHVgas: Lower heating value of the syngas

Vgas: Volume of the syngas

LHVbiomass: Lower heating value of the biomass

Cold gas efficiency depends on various parameters in the gasification process, such as gasifier design, feedstock type, and fuel moisture content. Cold gas efficiency increases with the rise in gas yield. It is defined as the ratio of the amount of energy produced per kilogram of product to the heating value of the fuel material. Cold gas efficiency is also an indicator of gasification performance, as it is influenced by both the heating value of the syngas and the volume of syngas generated from the fuel sample.

2.2. Calculation of the Heating Value of Syngas

The heating values of the syngas produced through gasification experiments were calculated based on the higher heating values (HHVs) of CO, H_2, and CH_4 components, as listed in Table 1. Sample calculations of the heating value are presented in the equations below.

Table 1. Heating Values of Hydrogen, Methane, and Carbon Monoxide Gases [30,31].

Gas	Higher Heating (HHV)				Lower Heating Value (LHV)			
	MJ/kg	MJ/m^3	kcal/m^3	kcal/kg	MJ/kg	MJ/m^3	kcal/m^3	kcal/kg
H_2	141	12	3035	33852	120	10	2,5	28,6
CH_4	55	39	9508	13259	50	35	8,5	8,5
CO	10	12	3014	2413	10	12	3	2,4

2.3. Reactor Design

In this study, a fixed-bed, downdraft gasification reactor was designed to allow controlled feeding of biomass at desired quantities, and to accommodate different temperatures and feed rates. A cyclone separator was added to the reactor outlet to remove unwanted components from the gas and to promote internal recirculation of the produced gas within the reactor for a more efficient process. The maximum reactor volume is 3 L, and it was specially manufactured from high-temperature-resistant AISI 310S stainless steel. The external wall of the reactor was wrapped with a ceramic jacket to enable indirect heating of the system.

The cyclone integrated into the reactor not only facilitates gas-solid separation but also removes dust, ash, tar, and other undesirable substances, thus improving thermal efficiency [32]. After leaving the cyclone unit, the syngas passes through sequential cooling columns, where volatile organic compounds are condensed and removed from the system. To further purify and enhance the quality of the gas, it is passed through an adsorption column and a ceramic filter, after which measurements are performed. The composition of CO, CO_2, H_2, CH_4, and O_2 in the syngas is measured using an online gas analyzer, and the heating value of the produced gas is calculated mathematically. The volumetric composition of the produced syngas is measured in real time every minute using a gas analysis device.

2.4. Gasification of Biomass Samples under Different Operating Conditions, Optimization of Process Parameters, and Syngas Production

In this study, three types of biomass waste were selected as feedstocks: sewage sludge, green waste, and olive pomace. In addition, a mixed waste sample was prepared by blending these three wastes in specific proportions. The selected wastes were subjected to waste characterization and pre-treatment.

The green waste, sewage sludge, and olive pomace used in the experiments were dried and homogenized. The moisture, ash, volatile matter, and fixed carbon contents of each feedstock and the prepared blend were determined in accordance with ASTM standards.

The fuel amount to be fed into the system was fixed at 75 g. As gasifying agents, both dry air and pure oxygen (O_2) were used. Based on the results of the gasification experiments conducted in the downdraft fixed-bed reactor, optimal operating conditions were determined, and a series of experiments were carried out accordingly. Dry air was fed into the system at flow rates of 0.05, 0.1, 0.2, and 0.4 L/min to observe the impact of flow rate variation on gasification performance. When determining the flow rate for pure oxygen, values corresponding to one-fifth of the highest-efficiency dry air flow rate were selected. Based on preliminary tests, the optimal flow rate of pure oxygen was determined to be 0.015 L/min.

To investigate the effect of temperature on gasification efficiency and syngas quality, gasification experiments were repeated at 700°C, 800°C, and 900°C.

3. Results

3.1. Analysis of Gasification Products

3.1.1. Gasification Conversion Rates

The mass-based gas conversion rates, along with the quantities of solid, liquid, and gaseous products obtained from the gasification experiments, are presented in Table 2 (GW: Green Waste, OP: Olive Pomace, SS: Sewage Sludge, MW: Mixed Waste).

Upon examining Table 2, it was determined that in the gasification experiments using different biomass sources, the gas conversion rate varied between 26% and 68%, depending on operational temperatures, types of gasifying agents, and their flow rates. It was also observed that the use of catalysts generally had a positive effect on gas formation and gas conversion efficiency.

Table 2. Amounts of Products and Gas Conversion Rates Resulting from Gasification Experiments

Sample	Temperature (°C)	Agent flow, dried air (L/min)	Solid Residue (g)	Liquid Product (g)	Syngas (g)	Gas Yield (%)
GW 75 g	700	0.05	22	16	37	49
	800	0.05	22	19	34	45
	900	0.05	22	18	34	45
	700	0.1	11	27	35	47
	800	0.1	22	10	43	57
	900	0.1	22	32	21	28
	700	0.2	13	17	44	58
	800	0.2	21	11	43	57
	900	0.2	19	25	31	41
	700	0.4	18	21	35	46
	800	0.4	20	10	45	60
	900	0.4	21	19	34	46
SS 75 g	700	0.05	34	10.77	29	39
	800	0.05	24	18	32	43
	900	0.05	32	14	29	38
	700	0.1	34	12	28	37
	800	0.1	34	9	31	41
	900	0.1	33	12	29	39
	700	0.2	34	13	27	37
	800	0.2	35	13	25	34
	900	0.2	35	14	26	34
	700	0.4	36	17	20	27
	800	0.4	35	15	25	33
	900	0.4	35	15	25	33
OP 75 g	700	0.05	20	35	20	26
	800	0.05	20	25	30	40
	900	0.05	20	25	30	40
	700	0.1	22	21	31	42
	800	0.1	20	20	35	46
	900	0.1	19	19	36	48
	700	0.2	21	29	25	33
	800	0.2	20	18	37	49
	900	0.2	21	26	28	37
	700	0.4	22	29	24	32
	800	0.4	20	21	34	45
	900	0.4	18	32	25	33
MW 75 g	700	0.05	25	18	32	42
	700	0.1	27	19	29	38
	800	0.05	25	10	40	53
	800	0.1	25	17	33	44
	900	0.05	25	9	41	54
	900	0.1	25	12	38	50
	700	0.015	18	8	49	65
	800	0.015	17	7	51	68
	900	0.015	20	8	47	62
SS 75 g	700	0.015	34	17	23	30
	800	0.015	33	16	25	33

	900	0.015	33	15	25	34
OP 75 gr	700	0.015	20	22	33	44
	800	0.015	19	22	34	45
	900	0.015	18	20	37	49
MW 75 gr	700	0.015	30	10	35	46
	800	0.015	26	7	42	56
	900	0.015	26	10	39	52

3.1.2. Elemental Analysis and Heating Value Results of Solid Products

In order to interpret the chemical changes in the solid products resulting from the gasification process conducted under the determined optimum conditions, the elemental analysis, calorific value, and loss-on-ignition analysis of the solid products are presented in Table 3.

Based on the analysis of elemental composition, heating value, and loss-on-ignition results, the carbon content of the gasification solid products was measured. It was found that there is a correlation between the heating value of the fuels and their carbon content, and that a certain amount of carbon still remains in the solid residue in a form that could potentially be further decompose

Table 3. Elemental Analysis, Heating Value, and Loss-on-Ignition Results of Solid Products

Experimental Conditions	**Elemental Analysis, % weight**					**Lower Calorific Value, MJ/kg**	**LOI (%)**
	C	**H**	**N**	**S**	**O**		
Green Waste, Dry Air, 900° C, 0.05 L/min	39.30	1.89	1.27	-	-	13.00	58
Green Waste, Pure Oxygen, 900° C, 0.015 L/min	36.10	1.10	0.55	-	-	14.75	61
Olive Pomace, Dry Air, 900° C, 0.05 L/min	73.05	1.36	0.19	-	-	22.30	64
Olive Pomace, Pure Oxygen, 900° C, 0.015 L/min	77.80	1.61	1.63	-	-	26.70	89
Sewage Sludge, Dry Air, 900° C, 0.05 L/min	69.10	1.07	1.57	-	-	24.00	75
Sewage Sludge, Pure Oxygen, 900° C, 0.015 L/min	69.20	1.25	1.49	-	-	23.70	70

3.1.3. Cold Gas Efficiency

Following the gasification experiments, the cold gas efficiency results were calculated using the measured gas volume, syngas heating value, and fuel heating value, and are presented in Table 4. Gas volume measurements and calculations were conducted for the gasification trials that yielded the best performance. For the syngas heating value calculations, the lower heating value (LHV) of the produced syngas, as described in the literature, was used.

According to Table 4, the maximum cold gas efficiency was 92% for green waste, 62% for olive pomace, and 73% for sewage sludge. The use of pure oxygen as the gasifying agent had a positive effect on cold gas efficiency.

Table 4. Cold gas efficiency

	(°C)	**Agent Flow Rate, Dry Air(L/min)**	**Gas volume (m^3/kg)**	**Calorific value of gas (kcal/m^3)**	**Fuel Calorific value (kcal/kg)**	**Cold Gas Efficiency (%)**
GW 75 g	900	0,05	80	2970	3810	83
	900	0,1	71	2850	3810	70
SS 75 g	900	0,05	45	2400	3020	47
	900	0,1	40	2470	3020	43
OP 75 g	900	0,05	52	3150	4140	52
	900	0,1	46	2900	4140	42
GW 75 g	900	0,015	83	3200	3810	92
SS 75 g	900	0,015	52	3200	3020	73

OP 75 g	900	0,015	60	3250	4140	62

3.2. Effect of Gasification Parameters

3.2.1. Effect of Gasifying Agent Flow Rate

The variation in the maximum composition of CH_4, CO, and H_2 gases with respect to the gasifying agent flow rate is illustrated in Figure 1.

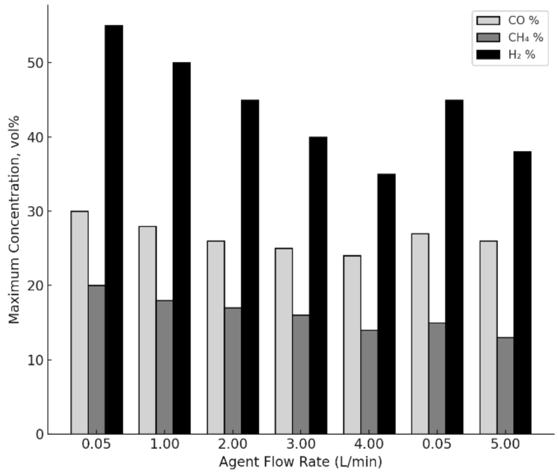

Figure 1. *Maximum Syngas Composition as a Function of Gasifying Agent Flow Rate*

As shown in Figure 1, the maximum composition of H_2 gas was achieved at a gasifying agent flow rate of 0.05 L/min using dry air, and it was observed that increasing the flow rate led to a decrease in H_2 composition. When pure oxygen was used as the gasifying agent, values approaching the maximum composition were also obtained. Similarly, the maximum CH_4 gas composition was reached at a flow rate of 0.05 L/min with dry air, and further increases in flow rate negatively affected its composition. For CO, higher gas compositions were recorded at flow rates of 0.05 and 0.1 L/min with dry air; however, increased flow rates reduced the CO content. The rise in flow rate tends to shift the system conditions closer to combustion, and similar results have been reported in the literature [33,34].

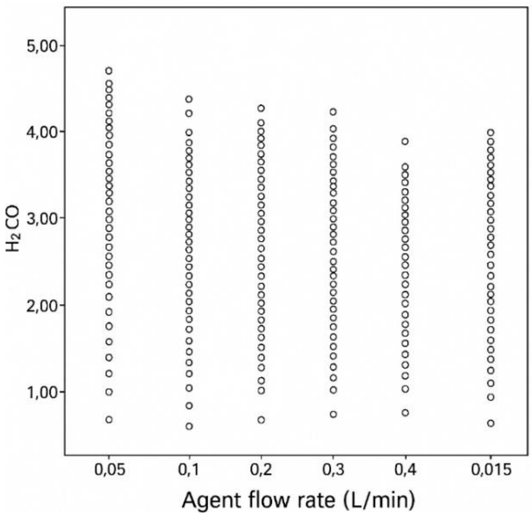

Figure 2. *Effect of Gasifying Agent Flow Rate on the Variation of H_2/CO Ratio*

Figure 2 illustrates the effect of gasifying agent flow rate on the variation of the H_2/CO ratio. The figure was constructed using experimental data from all conditions where the temperature was 700°C or higher.

The H_2 and CO ratios are critical parameters for converting product gases into valuable chemicals such as methanol and synthetic natural gas [35]. The water–gas shift reaction facilitates an increase in H_2 content and a corresponding decrease in CO content, thereby enhancing the H_2/CO ratio during the gasification process. CO reacts with steam according to the reaction below to form H_2 and CO_2 [36].

$CO+H_2O \rightarrow CO_2+H_2$ ΔH=- 41 kj/mole

For the water–gas shift reaction to proceed, the reaction must be exothermic. This is due to the fact that the gaseous product exiting the gasifier typically contains a significant amount of carbon monoxide and hydrogen. Under such conditions, the conversion of carbon monoxide to hydrogen takes place as part of syngas formation up to temperatures of 500°C, resulting in an increase in the H_2/CO ratio. According to Figure 2, the H_2/CO ratio is approximately 5 at a dry air flow rate of 0.05 L/min, but this value decreases as the flow rate increases. In gasification experiments conducted with pure O_2, the H_2/CO ratio reached a maximum of 4 at a flow rate of 0.015 L/min. It was determined that increasing the flow rate of the gasifying agent leads to a decrease in the H_2/CO ratio. Based on the data density in the graph, the H_2/CO ratio in gasification experiments was mostly observed between 1 and 3; however,depending on operational conditions, this ratio could vary beyond this range.

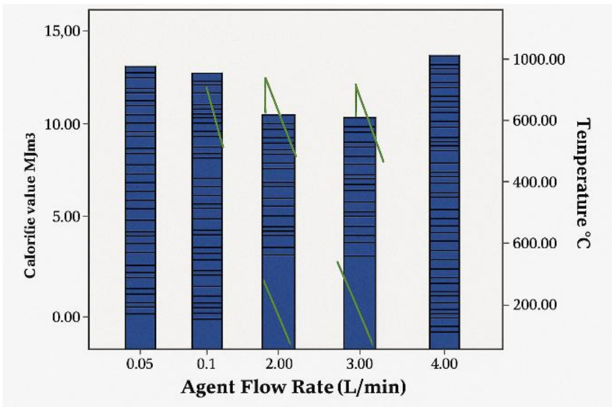

Figure 3. *Effect of Temperature and Gasifying Agent Flow Rate on Heating Value*

As shown in Figure 3, both temperature and gasifying agent flow rate have a significant impact on the heating value. An increase in flow rate results in a decrease in the heating value, whereas a rise in temperature leads to an increase in the heating value. It was specifically observed that dry air flow rates of 0.05–0.1 L/min and a pure oxygen flow rate of 0.015 L/min had a notable effect on the heating value. In all experiments conducted under optimum flow conditions, increasing the temperature was found to enhance both the syngas composition and its heating value.

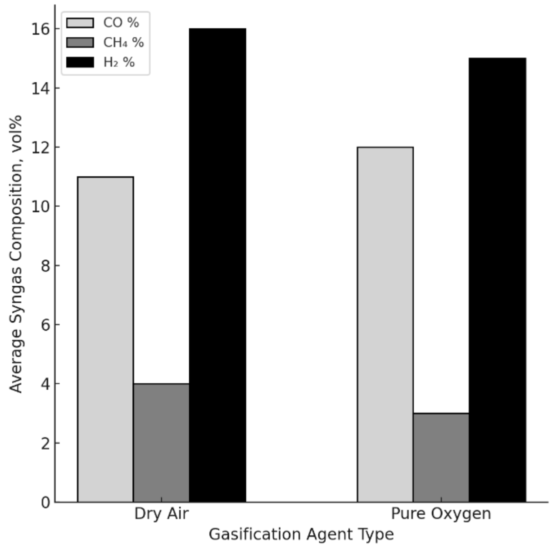

Figure 4. *Effect of Gasifying Agent Type on the Average Composition of CO, CH_4, and H_2 gases*

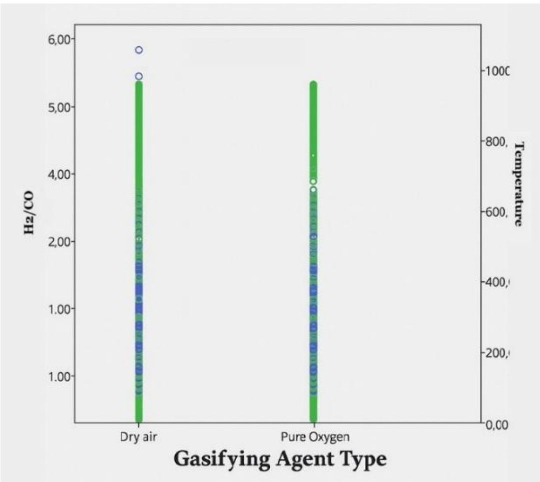

Figure 5. *Effect of Gasifying Agent Type on the H_2/CO Ratio*

As illustrated in Figure 4, the use of pure oxygen as the gasifying agent was found to increase both the average syngas composition and the volumetric percentage of hydrogen in the syngas. According to Figure 5, when evaluating the variation in the H_2/CO ratio based on the type of gasifying agent, higher ratios were observed at elevated temperatures during experiments conducted with dry air. In particular, for dry air gasification between 800°C and 900°C, the H_2/CO ratio ranged between approximately 5.5 and 6, while in experiments with pure O_2, this ratio was determined to be between 5 and 5.5. An H_2/CO ratio above 3 is typically interpreted as an indicator of hydrogen-rich syngas.

The highest syngas composition values in this study were obtained under low flow rates and high temperatures. Literature also reports that fixed-bed gasification systems are favorable for hydrogen production [37–39]. Several studies have shown that higher gasification efficiencies were achieved using dry air at lower flow rates [40,41]. In the green waste gasification experiments, a maximum of 45% H_2 by volume was obtained. Tanoh et al. [42] reported hydrogen contents close to 50% when gasifying a mixture of green waste and wood. In the produced syngas, a maximum of 35% CO and 5% CH_4 were recorded. In the case of olive pomace, the syngas contained up to 45% H_2 by volume. Tamošiūnas et al. [43], in their study on syngas production and energy recovery from olive pomace, reported maximum syngas compositions of 41% CO, 13% H_2, and 13.5% CO_2. When pure oxygen was used, the syngas heating value in an updraft reactor was measured at 13 MJ/Nm³. The optimum gasification temperature was determined as 900°C, and the best gasification conditions for a mixed biomass containing olive pomace were also achieved at 900°C [44], yielding 35% H_2 by volume—consistent with literature values in terms of both hydrogen content and optimal temperature.

The results indicated that biomass with high volatile matter, carbon content, and calorific value positively influenced combustible gas concentrations, calorific value, and energy efficiency [44]. However, since the results may vary depending on the amount and characteristics of the waste mixture, some deviations from literature values were also observed. In the gasification of sewage sludge, a maximum hydrogen concentration of 45% by volume was achieved. Chen et al. [45] reported 32% H_2 in syngas from co-gasification of sewage sludge and palm kernel shells. Studies have shown that the average activation energy for mixed fuels is lower than that for pure feedstocks. Gai et al. [46] reported 25–29% H_2 by volume in sewage sludge gasification. Feng et al. [47] observed syngas heating values of 12.5 MJ/Nm³ and hydrogen concentrations between 42% and 46% in steam gasification of sewage sludge using a fixed-bed reactor. Lee et al. [48] also reported 46% H_2. In a study by Hu et al. [49], 26% H_2 was obtained during catalytic steam gasification of sewage sludge at 800°C. With increased reaction temperature in catalytic gasification, this value rose to 46%. Similarly, Li et al. [50] achieved 38% H_2 at 800°C and increased it to 46% by raising the temperature to 1000°C. Overall, the syngas results obtained in this study were found to be consistent with those reported in the literature.

The H_2/CO ratio is a critical indicator for evaluating and optimizing the performance of gasification processes, as it is influenced by various operating parameters. This ratio is especially important when assessing the potential of syngas as a feedstock for methanol synthesis and other chemical processes [51,52]. An H_2/CO ratio greater than 3 indicates hydrogen-rich syngas. In this study, the H_2/CO ratio reached a maximum of 5 for green waste, 4 for olive pomace, and 6 for sewage sludge. For syngas-based chemical production, ratios of 2 or 1:2 are typically suitable. Syngas with an H_2/CO ratio above 3 is considered highly hydrogen-rich [53,54]. A ratio of 1 is suitable for hydroformylation, a chemical reaction involving the addition of carbon monoxide and hydrogen to an unsaturated compound (typically an alkene or alkyne). A ratio of 2 is ideal for Fischer–Tropsch synthesis of methanol and hydrocarbons [55]. Yang et al. [56] reported H_2/CO ratios between 0.9 and 4.7 for sewage sludge. Park et al. [57] found a ratio of approximately 2 in their biomass gasification experiments. Kong et al. [58] obtained ratios ranging from

1.77 to 3.35 when gasifying sewage sludge and agricultural biomass. While syngas is a key intermediate for various chemical products, a specific H_2/CO ratio is required to optimize the production of derived compounds. Thus, the H_2/CO ratio in syngas is particularly important in syngas-based chemical applications [59]. In conclusion, the H_2/CO ratios observed in syngas from different biomass sources were in good agreement with the literature and indicated that the produced syngas is hydrogen-rich and suitable for chemical applications.

The carbon content of the gasification products was measured, and it was found that there is a relationship between the fuel's heating value and its carbon content. A portion of carbon remains in the solid residue in a form that is still decomposable.

Cold gas efficiency (CGE) is defined as the ratio of the heating value of the syngas to that of the feedstock. Since it accounts only for the chemical energy potential of the produced gas, it is referred to as "cold" gas efficiency. CGE provides a measure of the effectiveness of the gasification process for further power applications. In this study, the maximum CGE was 92% for green waste, 62% for olive pomace, and 73% for sewage sludge. The use of pure oxygen as the gasifying agent positively influenced CGE. Jeong et al. [60] reported 83.01% CGE in co-gasification of coal and dried sewage sludge. Pedrazzi et al. [61] achieved an average CGE of 58% from green waste gasification. In another study involving gasification of plant-based waste, CGE was reported as 74.11% [62]. A separate study on municipal solid waste gasification reported CGE values as high as 85% [63]. In the case of olive pomace gasification, CGE was found to be around 70% [64]. The CGE values obtained in this study are generally in good agreement with those reported in the literature.

4. Conclusions and Recommendations

In this study, the production of valuable gaseous fuels—referred to as energy carriers—which can be recovered for national economic benefit, was investigated using various biomass sources such as sewage sludge, green waste, and olive pomace. For this purpose, a laboratory-scale fixed-bed downdraft gasification reactor was used in the experiments. The effects of different operating conditions and reactor configurations on syngas quality and cold gas efficiency were examined. Considering various influencing categories, the key findings of this study are summarized below:

In gasification experiments with green waste in a fixed-bed downdraft reactor, the net calorific value ranged between 7 and 12.8 MJ/m³, with a maximum gas conversion rate reaching 70%. The syngas composition contained up to 45% hydrogen by volume.

In sewage sludge gasification experiments, the net calorific value ranged between 5 and 12.8 MJ/m³, and the gas conversion rate reached a maximum of 45%. The syngas composition included up to 46% hydrogen by volume.

For olive pomace, the net calorific value ranged between 8 and 13.3 MJ/m³, and the gas conversion rate reached up to 50%. A maximum hydrogen content of 45% by volume was recorded in the syngas.

In gasification trials with different biomass feedstocks, depending on operational temperature, gasifying agent type, and agent flow rate, the calorific value ranged from approximately 5 to 14 MJ/kg, while gas conversion efficiency varied between 28% and 68%. The highest syngas composition values were achieved at low agent flow rates and high temperatures.

Post-gasification analyses revealed that a large portion of the carbon content in raw samples was successfully gasified. A correlation was observed between the carbon content and the heating value of the fuel, and some residual carbon was still present in a form that could be further decomposed.

In terms of H_2/CO ratio, maximum values were found to be 5 for green waste, 4 for olive pomace, and 6 for sewage sludge. These values indicate that the process is efficient and the resulting syngas is highly enriched in hydrogen. The results were found to be consistent with literature and show that such hydrogen-rich syngas can be utilized in chemical applications. Given the H_2/CO ratios achieved in this study, the resulting syngas can be considered suitable for direct use in internal combustion engines and gas turbines for CHP applications. In particular, the obtained H_2/CO ratios are within or near the optimal range for methanol synthesis, indicating the chemical synthesis potential of the syngas.

In this study, the cold gas efficiency reached a maximum of 92% for green waste, 62% for olive pomace, and 73% for sewage sludge. The use of pure oxygen as the gasifying agent had a positive effect on cold gas efficiency.

Gasification is a sustainable, clean, and environmentally friendly zero-waste process. The process aims to limit oxidation and reduce the formation of NO_x and SO_x emissions. Compared to other fuels, the calorific value of syngas produced through gasification is close to that of lignite coal, although it is lower than that of high-grade fuels. Nevertheless, achieving lignite-equivalent calorific value along with waste minimization makes this process both eco-friendly and advantageous.

The hydrogen-rich syngas generated under optimized conditions not only demonstrates high energy conversion efficiency but also offers versatile end-use options. It can be employed directly in gas turbines or internal combustion engines for renewable energy generation, and it serves as a key intermediate in chemical synthesis routes such as methanol and ammonia production.

In conclusion, energy and raw material recovery from alternative sources presents a viable model aligned with zero-waste and circular economy principles, particularly relevant for renewable energy and environmental technologies in our country. The outputs of this study can be further evaluated for full-scale applications. To facilitate this, pilot-scale implementations are essential. Additionally, enhancing syngas cleaning alternatives—such as the use of membrane systems—can improve the efficiency and effectiveness of the process. A comprehensive techno-economic analysis of the system will provide insights into the economic feasibility and practical applicability of the proposed approach.

Ultimately, this study demonstrated that high-efficiency energy production from biomass waste of different origins is achievable. Implementing waste-to-energy processes supports the core objectives of the circular economy by converting waste into valuable energy carriers. These approaches directly contribute to the zero-waste initiatives promoted nationally and globally. In particular, gasification—as one of the key zero-waste technologies—enables the recovery of hard-to-manage waste into economic value, while supporting sustainable development goals and climate change mitigation strategies.

Author Contributions

Research – Atakan ÖNGEN (AÖ), Nazlıcan YEŞİLOVA (NY); Experimental performance – AÖ, NY; Data collection – AÖ, NY; Data processing – AÖ, NY; Literature review – NY; Writing – AÖ, NY.

Conflict of Interest Statement

The authors declare that there is no conflict of interest with respect to the research, authorship, and/or publication of this article.

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