sustainability

MDPI

Article

Gasification and Power Generation Characteristics of Rice Husk, Sawdust, and Coconut Shell Using a Fixed-Bed Downdraft Gasifier

Md. Emdadul Hoque [1,*], Fazlur Rashid [1] and Muhammad Aziz [2]

[1] Department of Mechanical Engineering, Rajshahi University of Engineering & Technology, Rajshahi 6204, Bangladesh; frrashed10@gmail.com

[2] Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-Ku, Tokyo 153-8505, Japan; maziz@iis.u-tokyo.ac.jp

* Correspondence: emdadulhoque@gmail.com; Tel.: +880-1713-228615

Abstract: Synthetic gas generated from the gasification of biomass feedstocks is one of the clean and sustainable energy sources. In this work, a fixed-bed downdraft gasifier was used to perform the gasification on a lab-scale of rice husk, sawdust, and coconut shell. The aim of this work is to find and compare the synthetic gas generation characteristics and prospects of sawdust and coconut shell with rice husk. A temperature range of 650–900 °C was used to conduct gasification of these three biomass feedstocks. The feed rate of rice husk, sawdust, and coconut shell was 3–5 kg/h, while the airflow rate was 2–3 m^3/h. Experimental results show that the highest generated quantity of methane (vol.%) in synthetic gas was achieved by using coconut shell than sawdust and rice husk. It also shows that hydrogen production was higher in the gasification of coconut shell than sawdust and rice husk. In addition, emission generations in coconut shell gasification are lower than rice husk although emissions of rice husk gasification are even lower than fossil fuel. Rice husk, sawdust, and coconut shell are cost-effective biomass sources in Bangladesh. Therefore, the outcomes of this paper can be used to provide clean and economic energy sources for the near future.

Keywords: gasification; downdraft fixed-bed gasifier; rice husk; sawdust; coconut shell; bio-renewable energy; synthetic gas

Citation: Hoque, M.E.; Rashid, F.; Aziz, M. Gasification and Power Generation Characteristics of Rice Husk, Sawdust, and Coconut Shell Using a Fixed-Bed Downdraft Gasifier. *Sustainability* **2021**, *13*, 2027. https://doi.org/10.3390/su13042027

Academic Editor: Vincenzo Bianco

Received: 1 January 2021
Accepted: 9 February 2021
Published: 13 February 2021

1. Introduction

Global energy demand is increasing drastically with industrial development and human civilization [1–3]. As a consequence, consumption of world energy is increasing with a high growth rate of population and the industrial revolution, as shown in Figure 1.

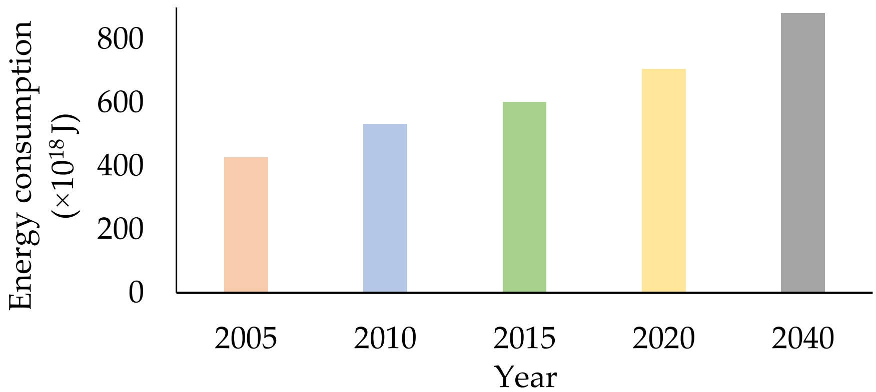

Figure 1. World energy consumption scenario from 2005–2040 [4].

Fossil fuels are the primary energy sources that are used to meet the high demand for world energy. However, the regeneration of fossil fuels is difficult, and they are limited in reserves. On the other hand, the cost of fossil fuels is increasing due to the high demand and low reserves of available energy sources [5,6]. Therefore, alternative sources of energy are required to find to fulfill the demand for future energy. Renewable energy sources, such as solar, wind, and biomass are believed to be potential energy sources in the future [6,7], and their utilization can reduce greenhouse gas emission, leading to the mitigation of global pollution.

In a similar way, the energy demand of the developing countries, like Bangladesh, is increasing due to their growing populations and economy, as shown in Figure 2 [8,9]. It is one of the densely populated countries in the world (1265/km^2 in 2020) [10].

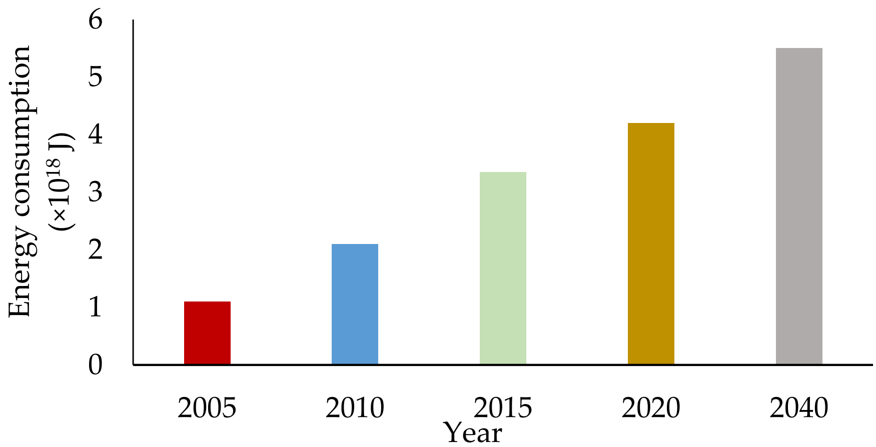

Figure 2. Energy consumption scenario from 2005–2040 in Bangladesh [8].

Conventional fossil fuels are the main sources of energy in Bangladesh (Figure 3). Currently, 65% of energy demand is covered by natural gas [11]. However, with the high demand for energy and low reserves of natural gas, it is urgently required to find new sources of energy [12].

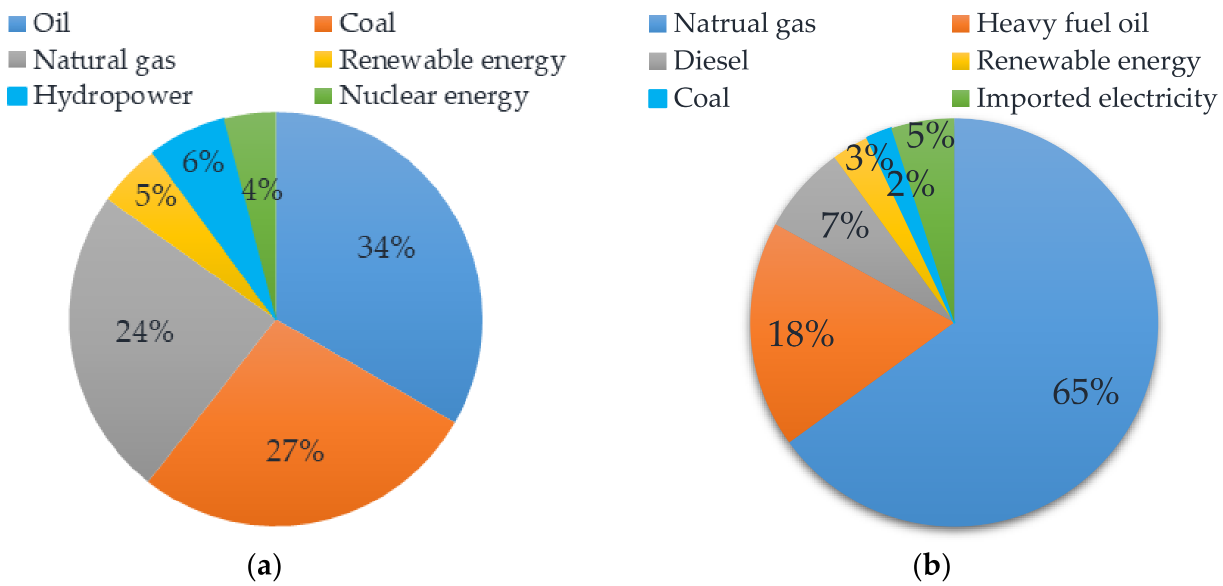

Figure 3. Primary energy sources to meet up (**a**) the global energy demand in 2020 [13] (**b**) the energy demand in Bangladesh for the year 2020 [11].

In Bangladesh, the majority of the household energy demand in rural and off-grid areas is fulfilled by agricultural residues. This is due to the reason that approximately 70% of economic developments are dependent on agricultural works. The land of Bangladesh is suitable for the generation of biomass. Biomass would be a potential alternative source of energy if it is appropriately utilized for power generation. At present, the most common sources of biomasses are wood, rice husk, sawdust, coconut shell, jute, and mustard.

Due to the lack of grid electricity supply, people in semi-urban and rural areas are dependent on biomass energy sources. Only around 10% of the total population has access to natural gas as energy sources. Table 1 presents different sources of energy for cooking in Bangladesh.

Table 1. Energy sources for cooking in percentage.

Energy Sources	2020	2010	2000
Cow dung	40.3	53.8	61.492
Wood	39.06	32.19	27.94
Kerosene	0.70	1.35	2.3
Natural gas	19.06	11.84	7.24
Electricity	0.40	0.55	1.02
Others (biogas)	0.48	0.27	0.008

However, the majority of power generation systems depend on natural gas by considering the huge availability of this source (Table 2). On the other hand, reserves of natural gas are limited. Therefore, alternative sources are required to fulfill future energy demand.

Table 2. Existing supply and capacity of power generation in percentage.

Energy Sources	Generation Capacity
Natural gas	~56
Coal	2.90
Heavy fuel oil	20.1
Hydroelectric	1.50
High-speed diesel oil	11.6
Others (solar, wind, biomass, etc.)	7.9

In Bangladesh, around 53% of the land is utilized for agricultural works, whereas ~18% are forest [14,15]. Residues generated from crops are left in agricultural land or forest after the process of harvesting. Additionally, crop residues remain unused as byproducts after the harvesting process in mills or industries [16]. Therefore, these unused and waste crop resources can be used as potential biomass energy sources. Rice husks, paddy straw, coconut shell, wheat straw, coconut husk, sawdust, sugar cane are the prime residues generated in the agricultural sector (Table 3).

Table 3. Agricultural residue generation as biomass sources.

Energy Sources	Generation in 2020 (Million Tons)
Rice husk	9.0
Sawdust	1.5
Coconut shell	0.40
Jute	1.1
Wheat	0.90
Maize	2.94
Mustard	0.34

Therefore, Bangladesh has a huge potentiality for biomass energy sources. Gasification can be used to generate power from biomass effectively and cleanly. The biomass gasification process can even be coupled with cogeneration units to generate electricity [17,18]. Biomass gasification can reduce global pollution, as well as mitigate the anxiety due to decreasing reserves of fossil fuels. Biomass contains cellulose, hemicellulose, and lignin that contribute to generate energy. Currently, renewable energy sources contribute to about 35% of the total energy required in developing countries. The major contributors to renewable energy sources are solar energy, hydroelectric energy, and wind energy. However, biomass and micro-hydro system contributes a small amount of energy for the national economy due to lack of proper utilization methods (Figure 4). Therefore, the current approach of biomass gasification would be a feasible solution of power generation from biomass.

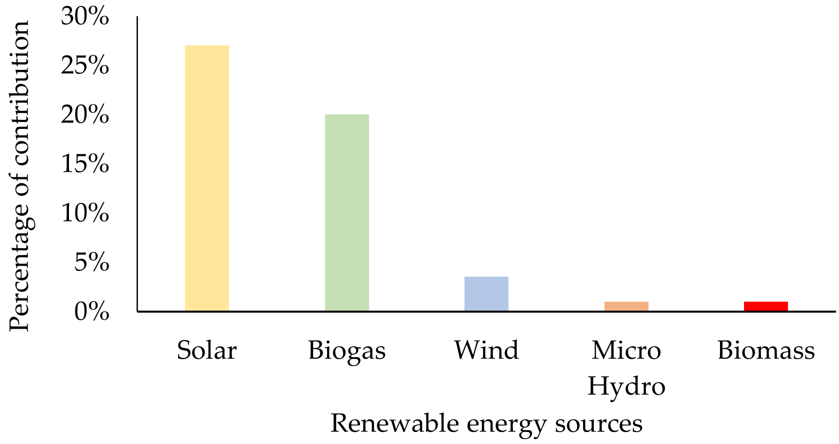

Figure 4. Contribution of renewable energy sources in Bangladesh for the year 2017 [19].

This paper presents and evaluates power generation characteristics using gasification technology. In this work, rice husk, sawdust, and coconut shell were used as biomass sources due to their higher heating value and availability. In addition, there are very few numbers of previous research works that showed the power generation characteristics and comparisons for rice husk, sawdust, and coconut shell. This paper shows the gasification of rice husk, sawdust, and coconut shell in a downdraft fixed-bed gasifier where these biomasses were moved downward due to their low weight and uniform size. This method improves the gasification efficiency which is less available in prior research. This paper also presents that the generated energy can be used to cover the energy demand in different areas, especially in off-grid rural areas in Bangladesh.

In this paper, gasification was used since it is an effective method for producing synthetic gas from biomass that includes mainly hydrogen (H_2), methane (CH_4), carbon di-oxide (CO_2), and carbon monoxide (CO). These components of synthetic gases are significant for internal combustion engines, boilers, fuel cells, and synthetic fuels. However, higher gasification efficiency, lower quantity of dust, and tar are key factors in gasification [20–23]. Considering these conditions, fixed and fluidized bed gasifiers are the most effective gasifiers. There are a number of different works in the literature that show the gasification of biomass in fluidized bed gasifiers [24–26]. Due to the cylindrical shape and flaky nature of the fluidized bed gasifier, it is very difficult and complex to fluidize rice husk, sawdust, and coconut shell during gasification. A fluidized bed gasifier requires forming a multi solid system that is complex in nature. However, most of the previous studies presented rice husk biomass gasification using a downdraft fixed-bed gasifier [27–29]. Previous research on sawdust and coconut shell biomass gasification using a downdraft fixed-bed gasifier is rare. No literature is found that compares and discusses the synthetic gas generation characteristics with their related cost analysis for rice husk, sawdust, and coconut shell using a fixed-bed downdraft gasifier.

Downdraft fixed-bed gasifiers generate low tar and dust with higher gasification efficiency [30,31]. The current method of biomass gasification can be utilized to generate energy using a sustainable technique that can increase the contribution of biomass to the national economy and fulfill the growing demand for energy. This paper also shows the effects of different variables and parameters that can be used to increase the production rate of synthetic gas in biomass gasification.

2. Materials and Methods

2.1. Biomass Gasification Using Fixed-Bed Gasifier

Gasification is the process where carbonaceous materials, such as biomass and coal, are converted to synthetic gas. In this process, organic solid/liquid compounds are converted to gas and solid phase. It is a thermochemical process where feedstock carbonaceous material is required to be heated up to a higher temperature [32]. The generated solid phase is known as char (carbon and ash) and the gas phase is called synthetic gas. Synthetic gas has the capacity to produce electricity and biofuel by its high heating power. Synthetic gas mainly consists of a mixture of CO, CO_2, H_2, CH_4, and tar. Figure 5 shows the flow diagram of the gasification process of rice husk, sawdust, and coconut shell that was used to generate power in the form of synthetic gas.

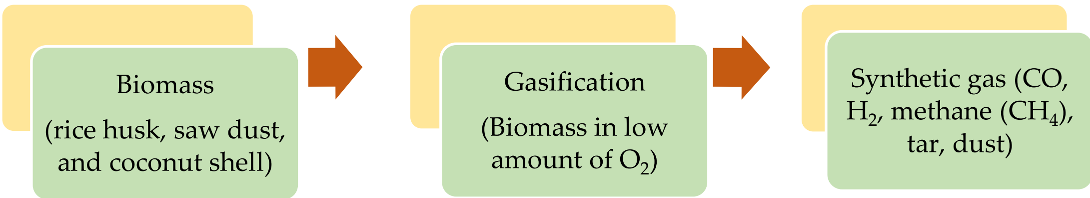

Figure 5. Flow diagram used during rice husk, sawdust, and coconut shell gasification.

The main reactions of the biomass gasification process are endothermic. The required amount of energy is generated from the oxidation of the biomasses through a thermal process. The principal steps of the biomass gasification method are oxidation (exothermic), drying (endothermic), pyrolysis (endothermic), and reduction (endothermic) as shown in Figure 6. However, the generated tar is needed to decompose to produce light hydrocarbons (HC) [33].

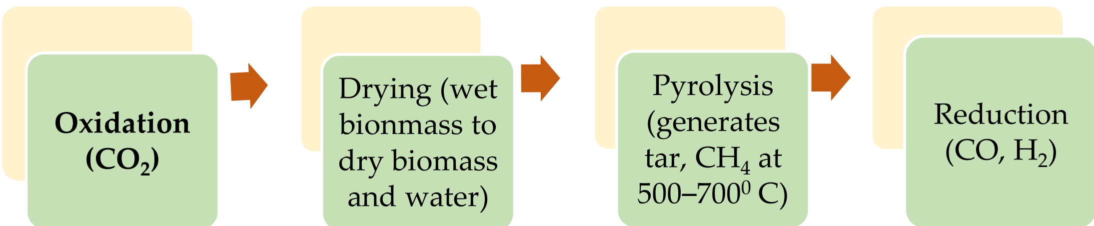

Figure 6. Biomass gasification process and reactions of gasifier.

The oxidation step is required to generate the energy for the endothermic drying process to maintain a specific operating temperature. This process is occurred with a deficient amount of oxygen than the stoichiometric ratio to oxidize a small portion of the fuel. The principal oxidation reactions are the following Equations (1)–(3) [33]:

$$\text{Combustion of char}: \; C + O_2 \rightarrow CO_2 \; \Delta H_f = -394 \text{ KJ/mol} \tag{1}$$

$$\text{Partial oxidation}: \; C + 1/2O_2 \rightarrow CO \; \Delta H_f = -111 \text{ KJ/mol} \tag{2}$$

$$\text{Combustion of hydrogen}: \; H_2 + 1/2O_2 \rightarrow H_2O \; \Delta H_f = -242 \text{ KJ/mol} \tag{3}$$

Therefore, the main component of the oxidation step is the energy (thermal) requires for the whole gasification process including drying, pyrolysis, and reduction. In addition, carbon dioxide (CO_2), carbon monoxide (CO), and water are the combustion products in the oxidation step.

After the oxidation step, the drying of the biomass (rice husk, sawdust, and coconut shell) occurs. In the drying process, the moisture contents in the biomass feedstocks are evaporated. The amount of necessary heat is proportional to the moisture contents in the biomass feedstock materials. The main drying reaction is the following Equation (4) [33]:

$$\text{Biomass (moisture contents)} \rightarrow \text{Biomass(dry)} + H_2O(g) \quad (4)$$

Rice husk contains 5–35% moisture that transforms into steam through pretreatment using an oven at 100–150 °C by the Equation (4). However, it is known that the drying step completes when the temperature of the biomass reaches 150 °C. In this work, biomass gasification was done at a temperature range of 650–900 °C.

The pyrolysis step consists of the decomposition of the carbonaceous biomass materials. It generates solid, liquid, and gaseous fractions where the range of solid fraction is 20–25 wt.%, liquid 1 wt.%, and 70–90 wt.% of gaseous fractions for the downdraft fixed-bed gasifier [33,34]. In this work, the pyrolysis step of the dried biomass took place inside the gasifier between 500–700 °C and air was supplied through the air control valve.

The pyrolysis step in biomass gasification process is the following Equation (5) [35]:

$$\text{Biomass feedstocks} \leftrightarrow CO + CO_2 + H_2 + H_2O + CH_4 + C_xH_y + \text{char} + \text{tar} \quad (5)$$

In the reduction step, all gaseous and char products of the oxidation and pyrolysis steps reacted with one another to form the final synthetic gas. The major reduction reactions are the following Equations (6)–(9):

$$\text{Boudouard reaction}: \ C + CO_2 \leftrightarrow 2CO \ \Delta H_f = 172 \text{ kJ/mol} \quad (6)$$

$$\text{Char reformation}: \ C + H_2O \leftrightarrow CO + H_2 \ \Delta H_f = 131 \text{ kJ/mol} \quad (7)$$

$$\text{Water gas shift}: \ CO + H_2O \leftrightarrow CO_2 + H_2 \ \Delta H_f = -41 \text{ kJ/mol} \quad (8)$$

$$\text{Methanation}: \ C + 2H_2 \leftrightarrow CH_4 \ \Delta H_f = -75 \text{ kJ/mol} \quad (9)$$

Among the four equations, reactions of Equations (6) and (7) are endothermic, while reactions of Equations (8) and (9) are exothermic. However, the Boudouard and char reformation reactions make the overall reduction step endothermic that needs energy from the oxidation step. The products and reactants in the reduction step are coexistent and maintained their ratios for concentration by thermodynamic laws.

The increase of temperature favors the reactions (6) and (7), while the low temperature helps the reactions (8) and (9). Therefore, reduction temperature has a significant effect on the composition of the synthetic gas. It is suggested that the oxidation step of char increases at high temperature and decreases the formation of tar. However, the decrease of the temperature is a key factor for the overall reduction step for the characteristics of synthetic gas and solid residues.

The decomposition of the generated tar occurred by the following Equation (10) where methane is produced as the product gas.

$$C_nH_m \leftrightarrow C_{n-x}H_{m-y} + H_2 + CH_4 + C \quad (10)$$

2.2. Biomass Feed Materials

Different types of biomass feed materials are available in Bangladesh, such as rice husk, rice straw, sawdust, coconut shell, and jute stalk, etc. Among different biomass materials, rice husk sawdust, coconut shell, etc. are the majority in content [36]. The gasification process can convert these biomasses to energy. Gasification and incineration methods can also be used to generate energy from waste plastics [37].

This study presents the power generation from rice husk, sawdust, and coconut shell that were prepared on a laboratory scale at Rajshahi University of Engineering & Technology, Bangladesh. Firstly, rice husk, sawdust, and coconut shell were collected from the local rice husk mill (Haque Auto Rice Mill, Sapura) and the local area in Rajshahi, Bangladesh.

Sawdust materials were crushed and, by using sawdust binder, sawdust pellets were produced. On the other hand, coconut shells were cut into small pieces of ~5 cm.

Ultimate and proximate analysis of rice husk, sawdust, and coconut shell was done to find the heating value of the biomass materials. Table 4 shows the ultimate and proximate analyses and heating values of rice husk, sawdust, and coconut shell that were obtained in the laboratory analysis of feedstock materials.

Table 4. Ultimate and proximate analyses and heating value of rice husk, sawdust, and coconut shell.

Biomass Material	Fixed Carbon (wt.%)	Volatile Matter (wt.%)	Carbon (wt.%)	Hydrogen (wt.%)	Oxygen (wt.%)	Nitrogen (wt.%)	Sulphur (wt.%)	Ash (wt.%)	Heating Value (MJ/kg)
Rice husk	18.1	64.9	39.6	5.2	36.8	0.37	0.044	22.1	16.7
Sawdust	17.8	78.6	49.58	6.7	46.4	0.15	0.07	1.2	18.23
Coconut shell	21.94	72.30	48.92	6.15	36.85	0.30	0.8	0.40	20.58

After preparing feedstock materials and doing ultimate as well as proximate analysis of rice husk, sawdust, and coconut shell, the experiment was ready to be conducted. Figure 7 presents the flow diagram of power generation from rice husk, sawdust, and coconut shell using a downdraft fixed-bed gasifier.

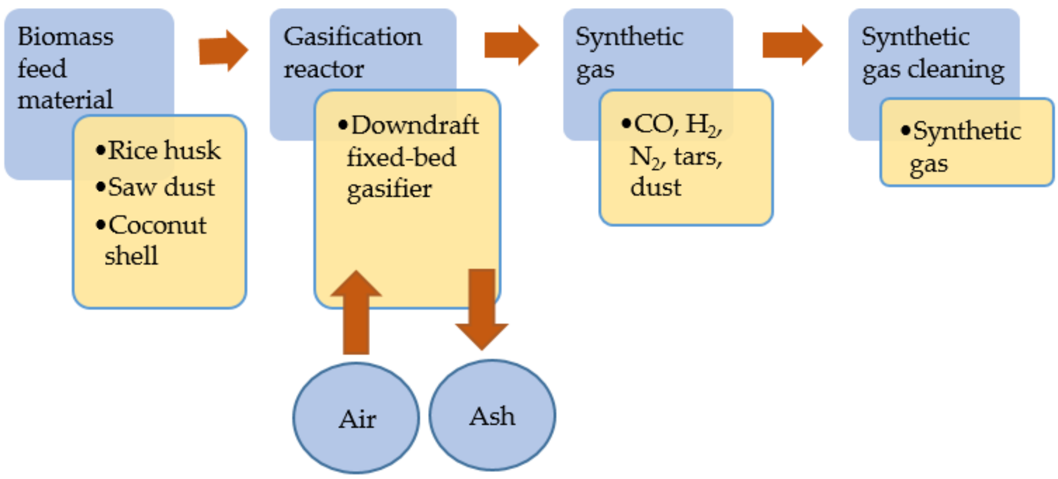

Figure 7. Flow diagram of the biomass gasification process.

2.3. *Fixed-Bed Downdraft Gasifier Unit*

In this work, a fixed-bed downdraft gasifier was used to conduct gasification as shown in Figure 8. Different parts were assembled together to carry out the experiment. The reactor was placed on a portable frame to make it easy to conduct the experiment anywhere in front of the fluid mechanics lab of Rajshahi University of Engineering & Technology, Bangladesh. The throat section was welded with the grate and bolted inside with the reactor collar to operate the gasifier easily and effectively. Asbestos ropes were wired outside the reactor to improve the insulation of the reactor.

In the experimental unit of the downdraft fixed-bed gasifier, a rotameter was connected with an air inlet pipe section with a gate valve to control the air flow rate, as shown in

Figure 8. Air was supplied through an air compressor and a ceramic gasket was used to make the gasifier tight sealed.

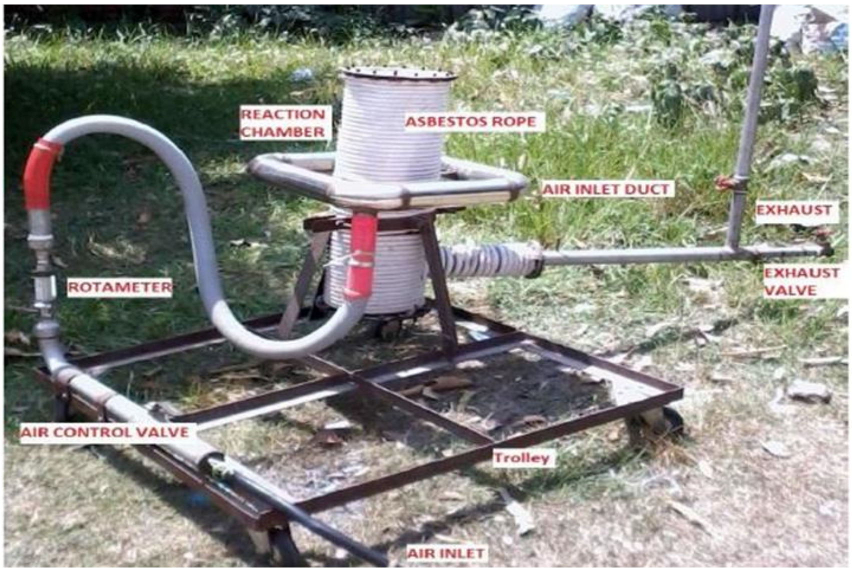

Figure 8. Photograph of the fixed-bed downdraft gasifier unit.

Figure 9 shows the gasification process flow diagram that followed during the gasification of rice husk, sawdust, and coconut shell.

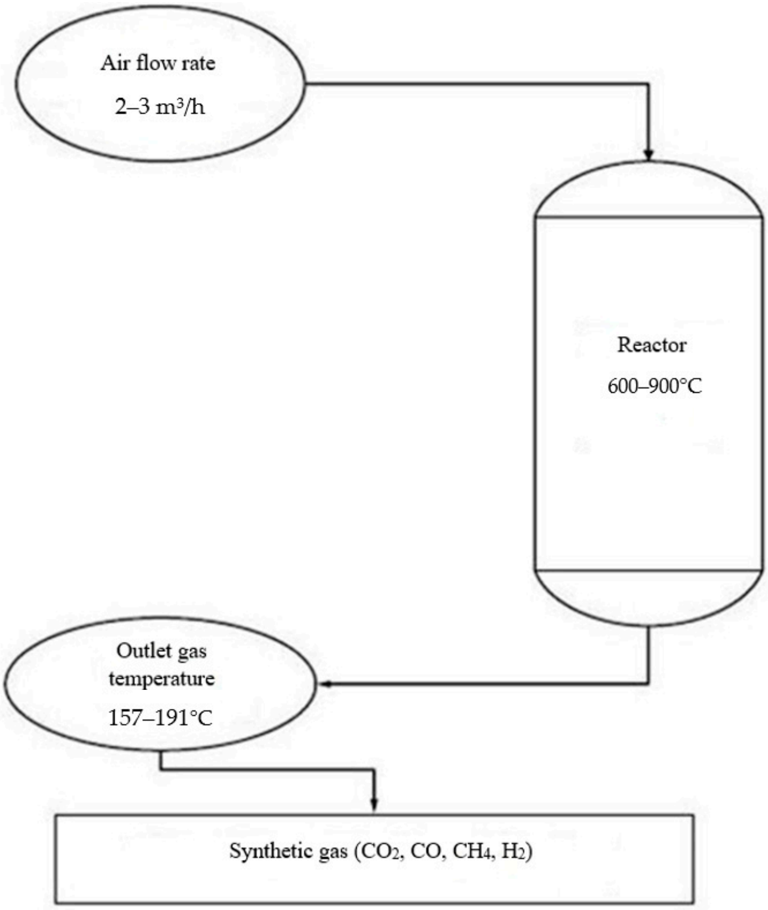

Figure 9. Flow Diagram of the fixed-bed downdraft gasifier unit.

2.4. Rice Husk, Sawdust, and Coconut Shell Gasification Experiment

The experiment was done on a lab-scale at Rajshahi University of Engineering & Technology, Bangladesh. Figure 10 shows the schematic diagram of the rice husk gasification in the downdraft fixed-bed gasifier used in this current study. The collected rice husk, sawdust, and coconut shells were moved down due to their low density and weight. Drying, pyrolysis, combustion, and reduction processes were taken place inside the gasifier, as shown in Figure 10.

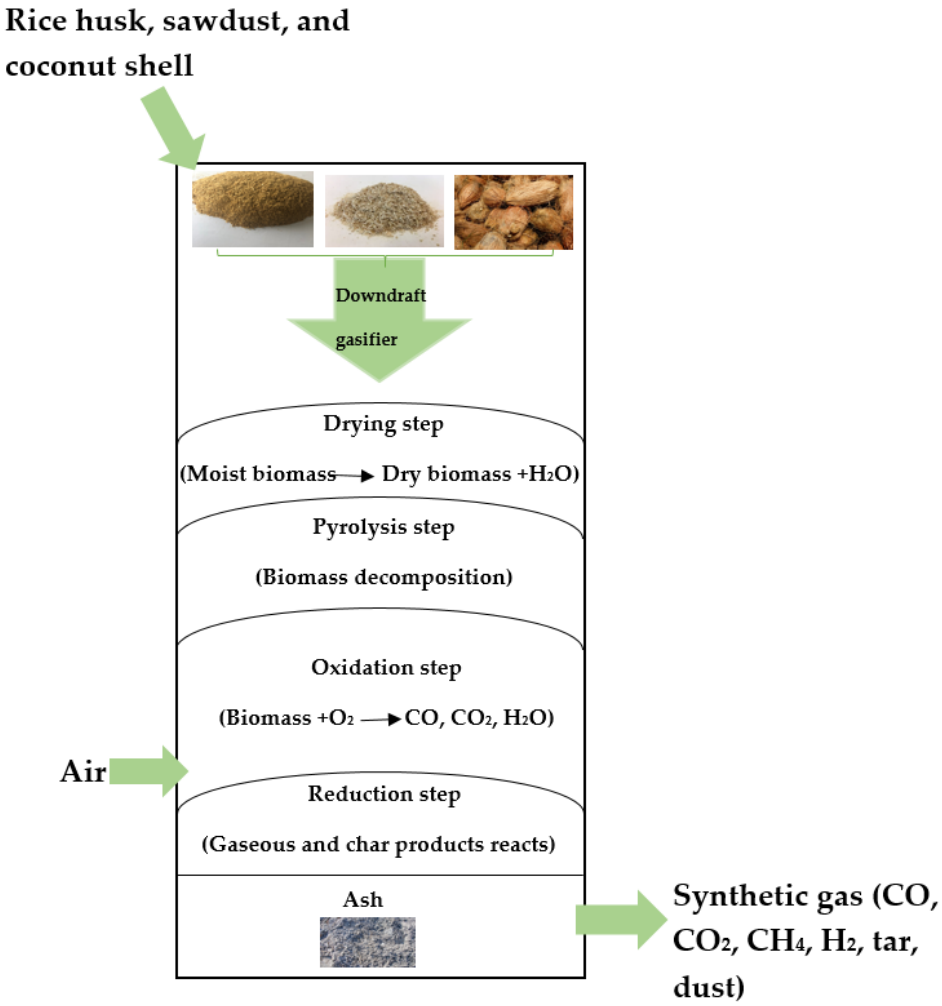

Figure 10. Schematic diagram of rice husk, sawdust, and coconut shell gasification.

Rice husk, sawdust, and coconut shell were fed from the top of the reaction chamber, as shown in Figure 10. The operating conditions of rice husk, sawdust, and coconut shell were set to be similar. A hopper was used to feed the biomass materials inside the combustion region of the downdraft gasifier. The air inlet and outlet were in the two opposite directions of the gasifier reactor, as shown in Figure 8. After combustion, the generated ash was disposed from the bottom of the gasifier and the exhaust outlet discharged the generated synthetic gas, as depicted in Figure 10.

In this work, the feed rate of rice husk, sawdust, and coconut shell was 36 kg/h, 4.0 kg/h, and 3.84 kg/h, respectively. Table 5 presents the operating conditions of rice husk, sawdust, and coconut shell gasification during the experiment.

Table 5. Operating conditions of rice husk, sawdust, and coconut shell gasification.

Biomass Material	Feed Rate (kg/h)	Flow Rate of Air (m^3/h)	Temperature of Gasifier (°C)
Rice husk	3.6	2.7	650–900
Sawdust	4.0	2.3	650–900
Coconut shell	3.84	2.3	650–900

In this experiment, rice husk, sawdust, and coconut shell were dried and partially combusted with a lower quantity of oxygen and at a higher gasification temperature. Throughout the experiment, the air flow rate and the rate of biomass feed material were maintained to generate less amount of tar. After pyrolysis, char and combusted gas were generated in the gasifier chamber and these gases were discharged from the lower part of the gasifier, as shown in Figure 10.

In this study, the flow rates of air were 2.7 m^3/h, 2.3 m^3/h, and 2.3 m^3/h for rice husk, sawdust, and coconut shell, as shown in Table 5. The reactor temperature of the gasifier was varied between 600–900 °C. The feed rates (3.6 kg/h, 4.0 kg/h, and 3.84 kg/h) were strictly maintained, and the reactor temperature was observed. However, the experiments were not stopped to check the temperature stabilization. By maintaining the constant feed rates throughout the experiment, the gasification of rice husk, sawdust, and coconut shell biomasses was done. Collected rice husk biomass was dried in an oven in the laboratory of Rajshahi University of Engineering & Technology, Bangladesh, for about 5–7 h at a temperature of 105–115 °C. However, the average moisture content of the collected rice husk was approximately 10%.

In the gasification, no steam was required to be fed to the gasifier as the collected and pretreated rice husk contained approximately 10% moisture that was enough for the rice husk gasification. Finally, the produced gas was collected from the exhaust port and processed for analysis using an infrared gas analyzer.

After gasification, the synthetic gas was analyzed with a gas analyzer. It involved several steps, firstly, the gas analyzer was calibrated for three (03) min. After that, the gas analyzer was ready to analyze the composition of synthetic gas produced in the gasification of rice husk, sawdust, and coconut shell. When the temperature increased to the limit of the gasification, it was time to start the synthetic gas formation, the gas analyzer was engaged with the output pipeline.

After that, data were collected for the composition of synthetic gas generated in the gasification of rice husk, sawdust, and coconut shell.

3. Results

In this study, a total of 5 kg rice husk was used, which took around 1.38 h for combustion during the gasification process. In addition, 5 kg sawdust and coconut shell were used. Sawdust took 1.25 h for combustion, and the flow rate was maintained at 4 kg/h. On the other hand, coconut shell required 1.3 h for combustion, and the flow rate was 3.84 kg/h. Figure 11 shows the reactor temperature of the gasification of rice husk, sawdust, and coconut shell. In this study, the maximum rice husk gasification reactor temperature was observed at 810 °C while the minimum temperature was found to be 650 °C. In contrast, maximum and minimum reactor temperatures of sawdust gasification were found at 860 and 660 °C, respectively. In addition, coconut shell gasification temperature varied between 661 and 875 °C. The synthetic gas was collected and analyzed for different time intervals between these two extreme temperatures. Although the rice husk was preheated in an oven for 5–7 h at a temperature of 105–115 °C, however, it took time, in the beginning, to combust and increase the reactor temperature. It is clear from Figure 11 that reactor temperature increases with the time of the gasification process. On the other hand, the reactor temperature of sawdust gasification was higher than the temperature of rice husk gasification.

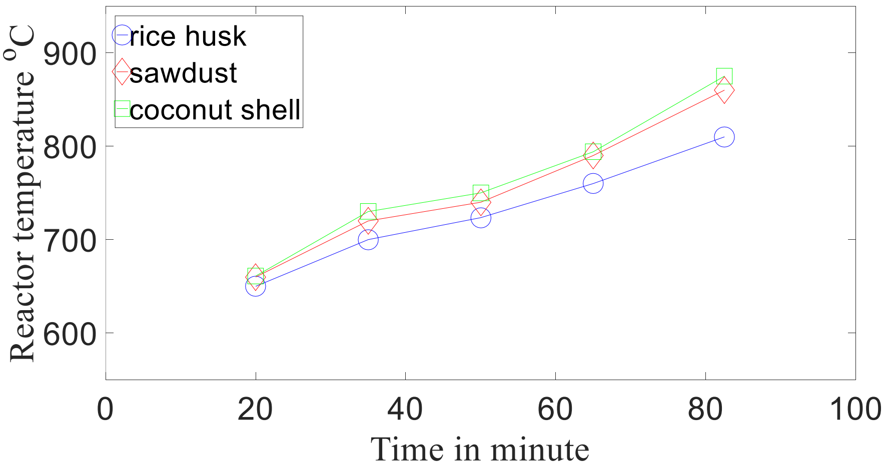

Figure 11. Combustion temperature during the rice husk, sawdust and coconut shell gasification process.

Figure 12 presents the composition of synthetic gas corresponding to the time that was generated during the gasification of rice husk using air as a gasification agent. It is shown in Figure 12 that the generation rate of H_2 was the highest compared to CO_2, CO, and CH_4. The average composition of synthetic gas in the gasification of rice husk was found to be 18.48 vol.% CO, 10.448 vol.% CO_2, 0.166 vol.% CH_4, and 14 vol.% H_2. These trends were statistically significant. The mean and standard deviation of synthetic gas components for rice husk gasification are shown in Figure 13. However, the average composition and generation trend of synthetic gas in rice husk gasification obtained during this study is almost similar to the generation trend and average values shown in [27].

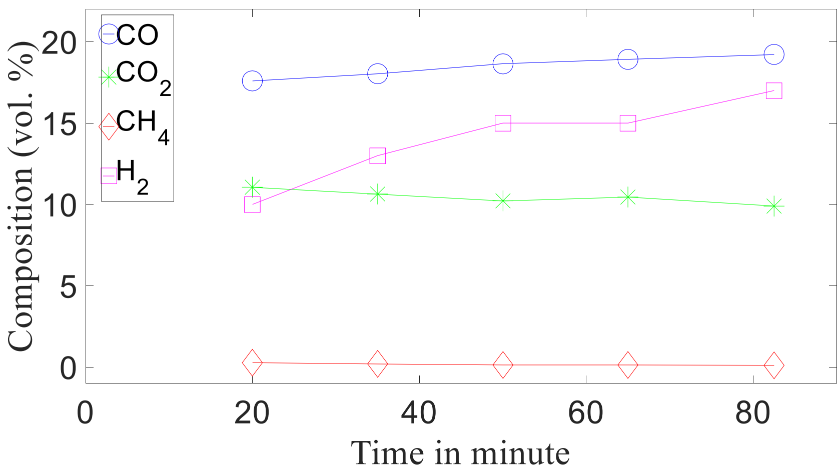

Figure 12. Synthetic gas composition in gasification of rice husk.

Figure 14 depicts the composition of synthetic gas corresponding to the time which was generated during the gasification of sawdust using air as a gasification agent. The average composition of synthetic gas in the gasification of sawdust was found 20.218 vol.% CO, 8248 vol.% CO_2, 0.916 vol.% CH_4, and 16.64 vol.% H_2. From Figure 14, it is shown that the compositions of generated H_2 and CH_4 are higher compared to the gasification of rice husk. In contrast, CO_2 generation is lower in the case of sawdust compared to the gasification of rice husk. Sawdust has higher contents of carbon and hydrogen (Table 1) compared to rice husk, leading to higher energy density. These trends were statistically significant. The mean and standard deviation of synthetic gas components for sawdust gasification are shown in Figure 15. Therefore, the composition of synthetic gas, especially in terms of CO and H_2, in the gasification of sawdust is better than rice husk.

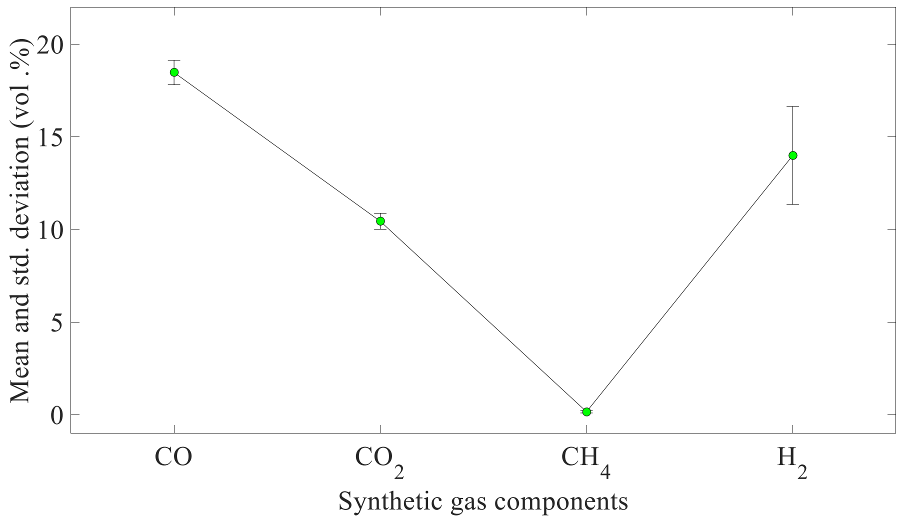

Figure 13. Mean and standard deviation of synthetic gas composition (vol.%) during rice husk gasification.

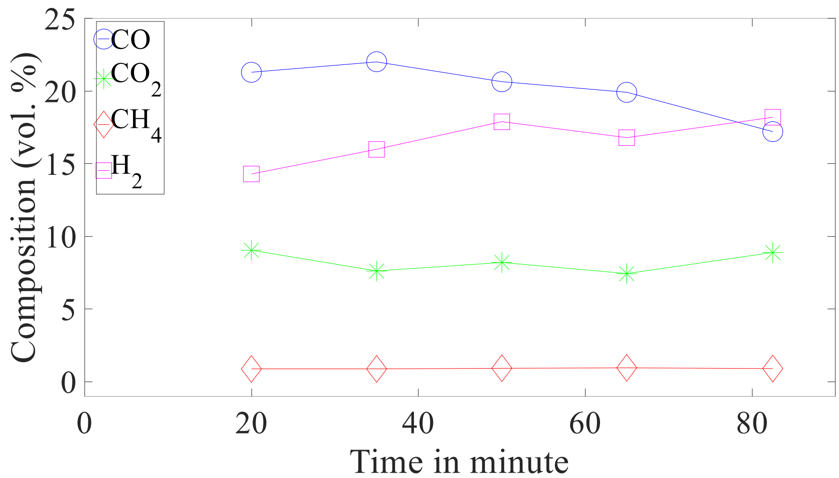

Figure 14. Synthetic gas composition in gasification of sawdust.

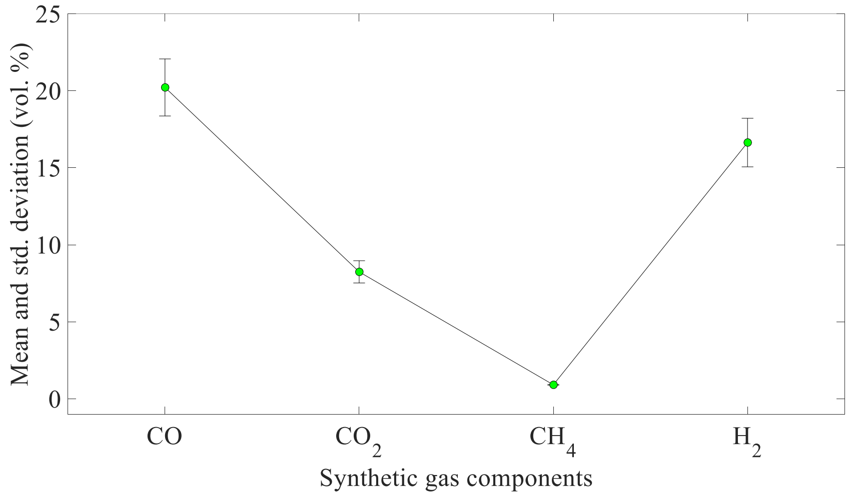

Figure 15. Mean and standard deviation of synthetic gas composition (vol.%) during sawdust gasification.

Figure 16 shows the composition of synthetic gas generated from the gasification of coconut shell using air as a gasification agent. The average concentrations of CO, CO_2, CH_4, and H_2 in the produced synthetic gas were 23.018, 7048, 1132, and 18.846 vol.%, respectively. The concentrations of produced H_2 and CH_4 are higher compared to the gasification of rice husk and sawdust, although the produced CO_2 concentration is lower compared to the gasification of rice husk. These trends were statistically significant. The mean and standard deviation of synthetic gas components for coconut shell gasification are shown in Figure 17. Coconut shell has higher volatile matter, carbon, and hydrogen contents, and energy density compared to rice husk. Therefore, the composition of synthetic gas in the gasification of coconut shells is better than rice husk. In addition, the produced CO is comparatively higher for coconut shell than that generated by the gasification of rice husk and sawdust. Table 6 presents the main components of the generated synthetic gas, lower heating value (LHV), and cold gas efficiency for rice husk, sawdust, and coconut shell. In the generated synthetic gas, the remaining percentage (average: rice husk 56.9%, sawdust 53.9%, and coconut shell 49.9%) of gases contains mainly nitrogen (N_2).

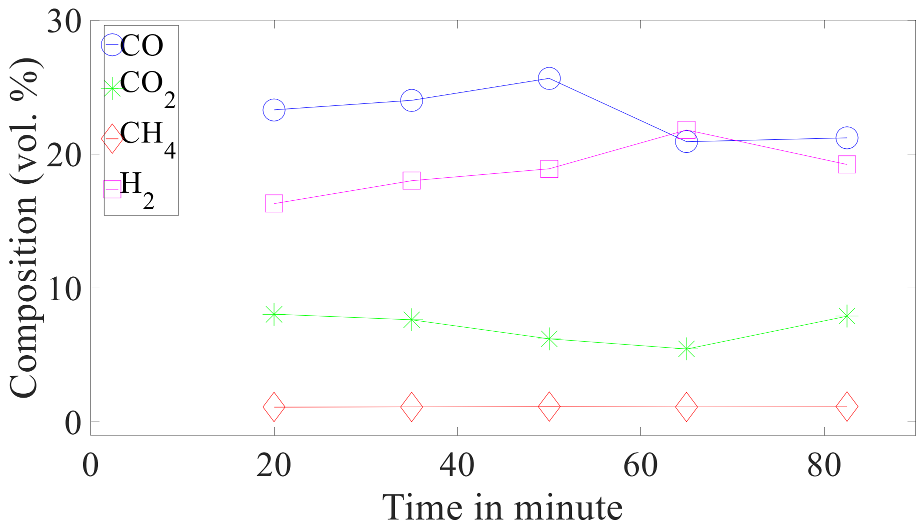

Figure 16. Synthetic gas composition in gasification of coconut shell.

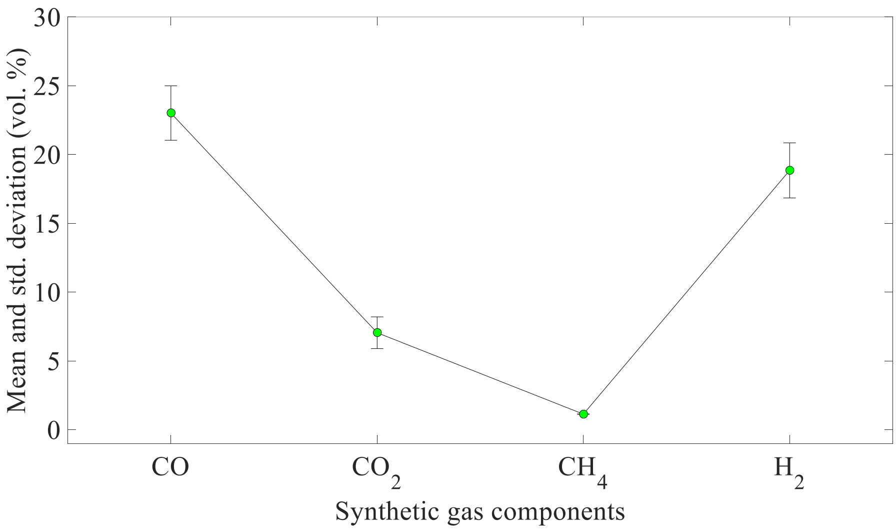

Figure 17. Mean and standard deviation of synthetic gas composition (vol.%) during coconut shell gasification.

Table 6. Performance characteristics of rice husk, sawdust, and coconut shell gasification.

Biomass	Mass of the Biomass (kg)	Yield of Synthetic Gas Components				Lower Heating Value (LHV) kcal/Nm^3	Cold Gas Efficiency (%)
		CO (vol.%)	CO_2 (vol.%)	CH_4 (vol.%)	H_2 (vol.%)		
Rice Husk	5	18.48 ± 0.66	10.45 ± 0.43	0.166 ± 0.07	14.0 ± 2.65	933.6	>60
Sawdust		20.22 ± 1.85	8.25 ± 0.72	0.92 ± 0.03	16.64 ± 1.58	1118.9	>70
Coconut shell		23.02 ± 1.98	7.05 ± 1.15	1.13 ± 0.015	18.84 ± 2.01	1278.18	>70

Figure 18 shows the outlet gas temperature of the gasification of rice husk, sawdust, and coconut shell. In this study, the maximum and minimum outlet gas temperatures of rice husk gasification were 178 and 157 °C, respectively. In contrast, the maximum and minimum temperature of outlet gas of sawdust was found at 188 and 160 °C, respectively. On the other hand, in the case of coconut shells, the maximum and minimum temperatures of outlet gas were 191 and 158 °C, respectively. It is shown in Figure 18 that the outlet gas temperature increases with the time of gasification. On the other hand, the outlet gas temperature of sawdust gasification was higher than one of rice husk, while coconut shell showed the highest outlet gas temperature.

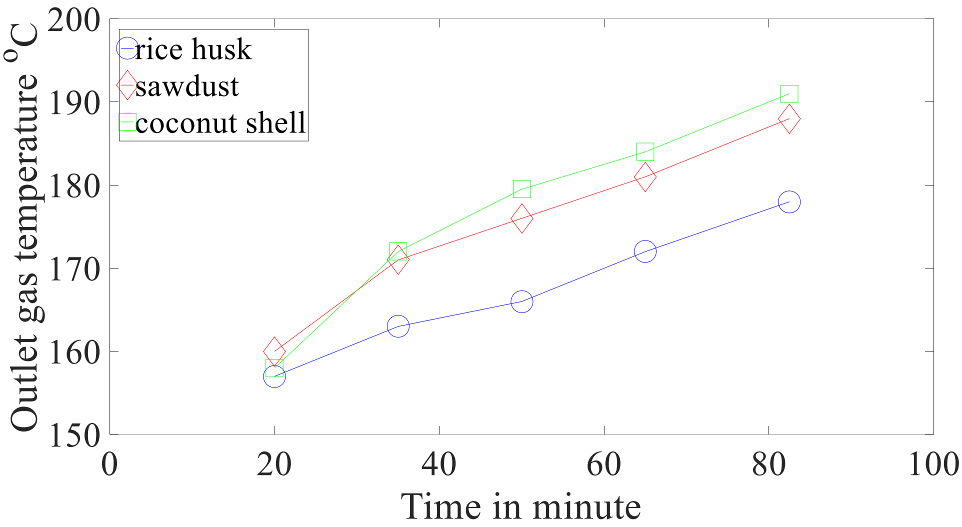

Figure 18. Outlet temperature of gasifier reactor for rice husk, sawdust, and coconut shell.

By using the composition of synthetic gas, it was found that the lower heating values of rice husk, sawdust, and coconut shell were approximately 9336, 1118.9, and 1278.18 kcal/Nm^3, respectively. These values are comparable with the heating values obtained in [38]. Moreover, this heating value of synthetic gas is even better than the heating value of rice husk gasification using an updraft gasifier obtained by Wittayakun et al. [39].

It was also found that both reaction temperature and heating value of biomass materials were the key factors that increased the efficiency of biomass gasification. Moreover, the temperature of the pyrolysis process during gasification was the key factor that increased the production rate of CH_4 in synthetic gas produced in rice husk, sawdust, and coconut shell gasification.

Cost analysis of rice husk, sawdust, and coconut shell showed that the overall cost of rice husk gasification was comparatively cheaper than sawdust and coconut shell. However, hydrogen generation was higher for coconut shell than rice husk and sawdust. On the other hand, coconut shell gasification provided lower emissions than rice husk gasification. Table 7 presents the cost analysis and environmental effect of rice husk, sawdust, and coconut shell gasification. Therefore, coconut shell gasification would be able to fulfill future energy demand and provide a cleaner environment.

Table 7. Cost and emission analysis for rice husk, sawdust, and coconut shell gasification.

Fuel Type	Cost ($) per 5 kg	CO_2 Generation vol.% (per 5 kg)	H_2 Generation vol.% (per 5 kg)
Rice husk	5.45	10.448	14.0
Sawdust	7.95	8.248	16.64
Coconut shell	9.36	7.048	18.846

4. Discussion

In this study, the gasification of rice husk, sawdust, and coconut shell was conducted and analyzed in an effort to cover and supplement the future energy demand in Bangladesh. This work added the gasification of coconut shell with rice husk and sawdust biomass feed materials. In Bangladesh, most of the rural areas are off-grid and they have no access to energy but have vast quantities of biomass sources, such as rice husk, wood, sawdust, and coconut shell. As a consequence, sustainable techniques of biomass gasification can make it possible to implement biomass plants that can provide energy for off-grid areas. In addition, the biomass gasification process can fulfill the high energy demand of the growing population in Bangladesh. Currently, biomass supplies around 73% of the total required energy in Bangladesh. In rural areas only approximately 5% of people use kerosene oil for cooking purposes, while the remaining people use biomasses as a cooking material.

The synthetic gas produced in the biomass gasification process is utilized to generate heat and power. This method of power generation is still at a beginning level in Bangladesh. The first power plant based on biomass (rice husk) was installed in the year 2007 with only two units of 125 kW capacity (total 250 kW). In contrast, there are 540 rice mills in active operation in Bangladesh that generate rice husk. It is estimated that the electrical power generation capacity of medium-sized rice mills that can generate rice husk of an average of 30 tons/day is 171 MW [8]. It is also approximated that around 3.34 million tons/year of sawdust generated in Bangladesh can be utilized to generate power and heat using the gasification process. Sawdust and coconut shell biomasses are significant in power generation and 41.26 million tons of these residues can generate 1178 MW of electricity [15].

Synthetic gas can also be burned inside a burner to generate heat or thermal energy. It can also be used as fuel in internal combustion engines. However, due to a lack of proper technology and implementation techniques, these sources are still at the infancy level in Bangladesh. Therefore, the experimental principal and gasification process of this work would help to set up a new power plant that can be operated by biomass feedstocks.

Outcomes of this study showed that emissions of rice husk, sawdust, and coconut shell gasification were lower when compared with fossil fuels such as diesel (per liter of diesel generates 2.6 kg CO_2). On the other hand, coconut shell generated the lowest quantity of emissions among the three studied biomass materials. Moreover, the power generation (hydrogen and methane) rate of rice husk, sawdust, and coconut shell gasification was significant compared to its cost.

In this study, gasification was shown only for a small laboratory-scale with a small number of feed materials. Hence, rice husk, sawdust, and coconut shell gasification utilizing a large quantity of biomass feed materials with a higher biomass feed rate (~50 kg/h) would be possible by applying a similar gasification mechanism. The generated power from rice husk, sawdust, and coconut shell gasification can be utilized to operate internal combustion engines, boilers, pumps, etc.

5. Conclusions

In this work, a downdraft fixed-bed gasifier was used for the gasification of rice husk, sawdust, and coconut shell. Natural air was supplied during the gasification as a gasification agent. The gasification was done under a reactor temperature of 650–900 °C and the outlet gas temperature was observed between 155–191 °C. In the case of coconut shell gasification, the mean composition of the generated synthetic gas was 23.02% CO, 7.05% CO_2, 1.13% CH_4, and 18.84% H_2. The heating value of the generated synthetic gas for the coconut shell gasification was 1278.18 kcal/Nm^3. However, the gasification of coconut shell leads to the highest concentration of CO, CH_4, and H_2 in the synthetic gas than rice husk and sawdust. In the case of sawdust gasification, the mean composition of the generated synthetic gas was 20.22% CO, 8.25% CO_2, 0.92% CH_4, and 16.64% H_2. The heating value of the generated synthetic gas for the sawdust gasification was 1118.9 kcal/Nm^3. On the other hand, in the case of rice husk gasification, the mean composition of the generated synthetic gas was 18.48% CO, 10.45% CO_2, 0.166% CH_4, and 14.0% H_2. The heating value of the generated synthetic gas for the rice husk gasification was 933.6 kcal/Nm^3. The cold gas efficiency for the rice husk gasification process was greater than 60%, while sawdust and coconut shells showed more than 70% efficiency. The fuel cost was highest for coconut shell ($9.36) when compared to rice husk ($5.45) and sawdust ($7.95). Overall, sustainable techniques of biomass gasification would make this source of energy a potential source of future energy for both developed and developing countries.

Author Contributions: All the authors have contributed substantially to the work reported. Conceptualization, M.E.H. and M.A.; methodology and experimentation, F.R.; data curation, M.E.H. and F.R.; writing—original draft preparation, F.R.; writing—review and editing, M.E.H. and M.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research is partially supported by JSPS KAKENHI Grant Number 19K04211.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are available in the paper.

Acknowledgments: Authors would like to acknowledge the Department of Mechanical Engineering, Rajshahi University of Engineering & Technology, Bangladesh for accessing the Fluid Mechanics laboratory to conduct the study of rice husk gasification.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sorrell, S. Reducing energy demand: A review of issues, challenges and approaches. *Renew. Sustain. Energy Rev.* **2015**, *47*, 74–82. [CrossRef]
2. Li, L.; Chen, C.; Xie, S.; Huang, C.; Cheng, Z.; Wang, H.; Wang, Y.; Huang, H.; Lu, J.; Dhakal, S. Energy demand and carbon emissions under different development scenarios for Shanghai, China. *Energy Policy* **2010**, *38*, 4797–4807. [CrossRef]
3. Hoque, M.E.; Rashid, F.; Prodhan, M.; Arman, A. Analysis of Energy Consumption and Efficiency to Reduce Power Losses in Industrial Equipment. In Proceedings of the International Conference on Mechanical Engineering, Dhaka, Bangladesh, 18–20 December 2017.
4. Ak, N.; Demirbas, A. Promising sources of energy in the near future. *Energy Sources Part A Recover. Util. Environ. Eff.* **2016**, *38*, 1730–1738. [CrossRef]
5. Saidur, R.; Abdelaziz, E.; Demirbas, A.; Hossain, M.; Mekhilef, S. A review on biomass as a fuel for boilers. *Renew. Sustain. Energy Rev.* **2011**, *15*, 2262–2289. [CrossRef]
6. Hoque, M.E.; Biswas, A.; Rashid, F.; Saad, A.M.; Bir, P.K. Production of electricity from renewable energy sources for home appliances and nano-grid. In Proceedings of the International Conference on Mechanical Engineering and Re-newable Energy, Chittagong, Bangladesh, 26–29 November 2015.
7. Pavlas, M.; Stehlik, P.; Oral, J.; Sikula, J. Integrating renewable sources of energy into an existing combined heat and power system. *Energy* **2006**, *31*, 2499–2511. [CrossRef]
8. Huda, A.; Mekhilef, S.; Ahsan, A. Biomass energy in Bangladesh: Current status and prospects. *Renew. Sustain. Energy Rev.* **2014**, *30*, 504–517. [CrossRef]
9. Uddin, M.S.; Islam, M.S.; Rashid, F.; Habibulla, I.M.; Haque, N. Energy and Carbon Footprint Analysis of Uni-versity Vehicles in Bangladesh. In Proceedings of the International Conference on Mechanical, Industrial and Materials Engineering, Rajshahi, Bangladesh, 28–30 December 2017.

10. Islam, M.K.; Alim, M.A.; Tsuji, N.; Mondal, M.M.H. An investigation into the distribution, host-preference and population density of ixodid ticks affecting domestic animals in Bangladesh. *Trop. Anim. Health Prod.* **2006**, *38*, 485–490. [CrossRef] [PubMed]
11. Uddin, M.; Rahman, M.; Mofijur, M.; Taweekun, J.; Techato, K.; Rasul, M. Renewable energy in Bangladesh: Status and prospects. *Energy Procedia* **2019**, *160*, 655–661. [CrossRef]
12. Rashid, F.; Hoque, M.E.; Peash, K.; Faisal, F. Performance analysis and investigation for the development of energy efficient building. In Proceedings of the International Conference on Mechanical Engineering and Renewable Energy, Chittagong, Bangladesh, 18–20 December 2017.
13. Asif, M.; Muneer, T. Energy supply, its demand and security issues for developed and emerging economies. *Renew. Sustain. Energy Rev.* **2007**, *11*, 1388–1413. [CrossRef]
14. Mondal, A.H.; Boie, W.; Denich, M. Future demand scenarios of Bangladesh power sector. *Energy Policy* **2010**, *38*, 7416–7426. [CrossRef]
15. Das, B.K.; Hoque, S.M.N. Assessment of the Potential of Biomass Gasification for Electricity Generation in Bangladesh. *J. Renew. Energy* **2014**, *2014*, 1–10. [CrossRef]
16. Bernard, F.; Prieur, A. Biofuel market and carbon modeling to analyse French biofuel policy. *Energy Policy* **2007**, *35*, 5991–6002. [CrossRef]
17. Galvagno, A.; Prestipino, M.; Maisano, S.; Urbani, F.; Chiodo, V. Integration into a citrus juice factory of air-steam gasification and CHP system: Energy sustaina-bility assessment. *Energy Convers. Manag.* **2019**, *193*, 74–85. [CrossRef]
18. Aziz, M.; Oda, T.; Kashiwagi, T. Advanced Energy Harvesting from Macroalgae—Innovative Integration of Drying, Gasification and Combined Cycle. *Energies* **2014**, *7*, 8217–8235. [CrossRef]
19. Mohammad, H. Achieving sustainable energy targets in Bangladesh. *UN Chron.* **2013**, *52*, 36–39. [CrossRef]
20. Sun, S.; Zhao, Y.; Ling, F.; Su, F. Experimental research on air staged cyclone gasification of rice husk. *Fuel Process. Technol.* **2009**, *90*, 465–471. [CrossRef]
21. Li, J.; Liu, J.; Liao, S.; Yan, R. Hydrogen-rich gas production by air–steam gasification of rice husk using supported nano-NiO/γ-Al_2O_3 catalyst. *Int. J. Hydrog. Energy* **2010**, *35*, 7399–7404. [CrossRef]
22. Yoon, S.J.; Choi, Y.-C.; Lee, J.-G. Hydrogen production from biomass tar by catalytic steam reforming. *Energy Convers. Manag.* **2010**, *51*, 42–47. [CrossRef]
23. Prabowo, B.; Aziz, M.; Umeki, K.; Susanto, H.; Yan, M.; Yoshikawa, K. CO_2-recycling biomass gasification system for highly efficient and carbon-negative power genera-tion. *Appl. Energy* **2015**, *158*, 97–106. [CrossRef]
24. Natarajan, E.; Nordin, A.; Rao, A. Overview of combustion and gasification of rice husk in fluidized bed reactors. *Biomass Bioenergy* **1998**, *14*, 533–546. [CrossRef]
25. Mansaray, K.; Ghaly, A.; Al-Taweel, A.; Hamdullahpur, F.; Ugursal, V. Air gasification of rice husk in a dual distributor type fluidized bed gasifier. *Biomass Bioenergy* **1999**, *17*, 315–332. [CrossRef]
26. Loha, C.; Chattopadhyay, H.; Chatterjee, P.K. Thermodynamic analysis of hydrogen rich synthetic gas generation from fluidized bed gasification of rice husk. *Energy* **2011**, *36*, 4063–4071. [CrossRef]
27. Yoon, S.J.; Son, Y.-I.; Kim, Y.-K.; Lee, J.-G. Gasification and power generation characteristics of rice husk and rice husk pellet using a downdraft fixed-bed gasifier. *Renew. Energy* **2012**, *42*, 163–167. [CrossRef]
28. Ma, Z.; Ye, J.; Zhao, C.; Zhang, Q. Gasification of rice husk in a downdraft gasifier: The effect of equivalence ratio on the gasification per-formance, properties, and utilization analysis of byproducts of char and tar. *BioResources* **2015**, *10*, 2888–2902. [CrossRef]
29. Khonde, R.; Chaurasia, A. Rice husk gasification in a two-stage fixed-bed gasifier: Production of hydrogen rich syngas and kinetics. *Int. J. Hydrogen Energy* **2016**, *41*, 8793–8802. [CrossRef]
30. Beenackers, A. Biomass gasification in moving beds, a review of European technologies. *Renew. Energy* **1999**, *16*, 1180–1186. [CrossRef]
31. Phuphuakrat, T.; Nipattummakul, N.; Namioka, T.; Kerdsuwan, S.; Yoshikawa, K. Characterization of tar content in the syngas produced in a downdraft type fixed bed gasifi-cation system from dried sewage sludge. *Fuel* **2010**, *89*, 2278–2284. [CrossRef]
32. Franco, C.; Pinto, F.; Gulyurtlu, I.; Cabrita, I. The study of reactions influencing the biomass steam gasification process. *Fuel* **2003**, *82*, 835–842. [CrossRef]
33. Molino, A.; Chianese, S.; Musmarra, D. Biomass gasification technology: The state of the art overview. *J. Energy Chem.* **2016**, *25*, 10–25. [CrossRef]
34. Lv, P.; Xiong, Z.; Chang, J.; Wu, C.; Chen, Y.; Zhu, J. An experimental study on biomass air–steam gasification in a fluidized bed. *Bioresour. Technol.* **2004**, *95*, 95–101. [CrossRef] [PubMed]
35. Widyawati, M.; Church, T.L.; Florin, N.H.; Harris, A.T. Hydrogen synthesis from biomass pyrolysis with in situ carbon dioxide capture using calcium oxide. *Int. J. Hydrogen Energy* **2011**, *36*, 4800–4813. [CrossRef]
36. Hoque, M.E.; Rashid, F.; Aziz, S.S.; Rahman, M.N.; Das, P. Process analysis and gasification of rice husk by using downdraft fixed bed gasifier. In *AIP Conference Proceedings*; AIP Publishing LLC.: Melville, NY, USA, 2019; Volume 2121, p. 130005. [CrossRef]
37. Mourshed, M.; Masud, M.H.; Rashid, F.; Joardder, M.U.H. Towards the effective plastic waste management in Bangladesh: A review. *Environ. Sci. Pollut. Res.* **2017**, *24*, 27021–27046. [CrossRef]

38. Jain, A.K.; Goss, J.R. Determination of reactor scaling factors for throatless rice husk gasifier. *Biomass Bioenergy* **2000**, *18*, 249–256. [CrossRef]
39. Wittayakun, J.; Khemthong, P.; Prayoonpokarach, S. Synthesis and characterization of zeolite NaY from rice husk silica. *Korean J. Chem. Eng.* **2008**, *25*, 861–864. [CrossRef]