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Experimental Study on Soaked Corn Cobs as Feedstock for Biomass Gasification in an Open Downdraft Gasifier

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Abstract. *Fossil fuels, which account for 83% of Indonesia's total energy supply, are depleting and environmentally unsustainable. Corn cob biomass, with an annual yield of 4.34 million metric tons, presents a viable alternative. Through gasification at temperatures of 700–1200°C, corn cobs can be converted into combustible gas or syngas. To enhance syngas yield, the corn cob gasification process can be optimized by increasing moisture content through soaking. However, experiments with soaked corn cobs have shown a significant decline in temperature and gasification zone performance. The gasification temperature decreased from 1024°C to 614°C, falling below the 700°C threshold. Additionally, the gasification zone shifted significantly downward in the reactor. This reduction is attributed to the high moisture content of the corn cobs, which exceeded 30%, reaching 56.78%, allowing the gasification process to last for 48 minutes. Before the gasifier ceased operation, syngas production achieved a promising average thermal power of 1.76 kW with an efficiency of 7.14%. These findings indicate that soaked corn cobs can serve as biomass gasification feedstock, provided the moisture content does not exceed 30%.*
Keywords: *gasification; corn cob; soaked; syngas; temperature.*

Type of the Paper: Regular Article.

1. Introduction

Indonesia's energy demand has been increasing at an annual rate of 6.29%, driven by economic growth, population expansion, industrial advancements, and technological progress. Projections estimate that energy demand, which was 1,853 million barrels of oil equivalent in 2023, will rise to 3,589 million by 2050 a substantial increase of 193.73% [1]. In 2023, fossil fuels supplied 1,537 million barrels of oil equivalent, comprising 83% of Indonesia's energy supply [2]. With fossil fuel reserves expected to be depleted within 70 years, biomass has been identified as a potential alternative energy source [3,4]. Biomass, as a renewable and environmentally friendly energy source, has the potential to supplement fossil fuels, reduce greenhouse gas emissions, and mitigate global warming [5–7].

Climate change is one of the most pressing global challenges, driven primarily by rising atmospheric carbon dioxide (CO_2) levels. As a potent greenhouse gas, CO_2 is largely emitted from fossil fuels combustion, which dominates global energy consumption [8]. The Paris Agreement marks a significant step in addressing this challenge [9]. Climate change affects not only the

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natural environment but also human health [10,11].

Advancements in renewable energy technologies have diminished the reliance on fossil fuels, offering a more sustainable energy future and a solution to climate change [12]. Biomass stands out as a promising alternative due to its abundance and diverse typology. Biomass comprises a diverse range of organic materials, including agricultural waste, that can be converted into electricity, heat, and biofuels [13,14]. Compared to fossil fuels, biomass offers several advantages. Firstly, biomass can be produced in a relatively short period, unlike fossil fuels, which require millions of years to form [15,16]. Secondly, it generates minimal greenhouse gas emissions and air pollution [17]. With abundant natural resources and substantial organic waste production, Indonesia has significant potential for biomass energy development, estimated at 735 MW [18].

Corn cobs represent a promising biomass resource with significant potential. As an agricultural residue from corn production, they remain largely underutilized. Currently, their use is limited to small-scale applications, such as animal feed, craft materials, and fuel briquettes. Harnessing corn cobs for energy production offers a promising approach to converting underutilized agricultural residues into a valuable resource. Purohit et al. [5] reported that cob waste constitutes 30% of the weight of harvested maize kernels [19]. According to the Central Bureau of Statistics [6], maize grain production totals 14.46 million metric tons, generating an estimated 4.338 million metric tons of cob waste [20]. This indicates that corn cob waste represents a valuable resource, particularly as a renewable energy source that can be converted into electricity through gasification [21,22].

Biomass gasification is a thermochemical process that converts solid materials derived from living matter, particularly agricultural waste, into combustible gas [7,8]. At high temperatures, biomass (CH_xO_y) undergoes chemical decomposition, producing carbon monoxide (CO) and hydrogen gas (H_2), collectively known as syngas [9,10]. Biomass gasification is most effective at temperatures above 700 °C [11]. In downdraft gasifiers, the process typically occurs in four stages: drying, pyrolysis, oxidation, and reduction, as illustrated in Fig. 1 [11–14].

The water content in biomass feedstock can enhance hydrogen gas production in gasification. At temperatures above 700°C, water reacts with charcoal to generate hydrogen and carbon monoxide [15]. This reaction increases the syngas heating value by up to 48% [16,17]. Water is typically introduced by injecting water vapor into the reduction zone, a process requiring specialized equipment [18]. Consequently, using soaked biomass as gasification feedstock presents a simpler alternative. Experimental studies have shown that soaking palm kernel shells enhances the effectiveness of the gasification process compared to their dry state [19–21]. However, high-moisture biomass poses a challenge, as excess water absorbs significant heat energy during gasification [22]. Corn cobs are a light and porous biomass capable of absorbing significant amounts of water. As a result, soaked corn cobs require substantial heat to reach gasification temperatures, particularly during the phase transition from liquid to vapor.

Corn cobs can serve as a value-added raw material in various industries. For instance, in the animal feed industry, they are commonly used as a high-fiber feed additive [23]. Utilizing this agricultural waste can create new business opportunities for farmers, thereby contributing to community economic growth. From an environmental perspective, utilizing corn cobs helps mitigate agricultural waste, which, if unmanaged, may contribute to pollution. Rather than being discarded or burned—practices that can cause air pollution—corn cobs can be processed into environmentally friendly products, such as biomass briquettes, serving as a renewable energy source [24].

This study aims to assess the feasibility of using soaked corn cob biomass as a gasification feedstock without requiring a drying pretreatment. A higher hydrogen content in syngas is anticipated due to the increased moisture in the feedstock. Additionally, eliminating the drying process could simplify syngas production. These benefits can be realized if the gasifier's thermal balance is maintained within the operational range, as high-moisture feedstock tends to lower the gasification temperature. Given the limitations of the available measurement tools, observations in this study were restricted to gasification temperature, biomass combustion heat rate, syngas combustion heat rate in the steam boiler, and system efficiency.

2. Materials and Methods

2.1. Biomass Gasification Performance

This study experimentally examined the gasification performance of soaked corn cob feedstock in an open downdraft gasifier. The observed performance include:

2.1.1. Gasifier temperature profile

The preferred gasification temperature range is 700–1,200 °C [13,23], with an ideal range of 1,000–1,200 °C to maximize syngas production and break down undesirable tar [24,25]. However, temperatures exceeding 1,200 °C may lead to the formation of harmful NO_x gases [26,27].

The gasifier must maintain sufficient temperature to sustain endothermic gasification reactions. The oxidation zone generates heat, raising the temperature while producing CO_2 and gaseous H_2O for subsequent gasification reactions. The temperature profile of the gasifier identifies the locations of the oxidation and reduction zones, serving as an indicator of gasification performance [20,28]. The sustainability of the gasification process is ensured when the reactor temperature remains above 700 °C, as indicated by the presence of flames in the flare [28]. The observed gasification temperature profile is illustrated in Fig. 1.

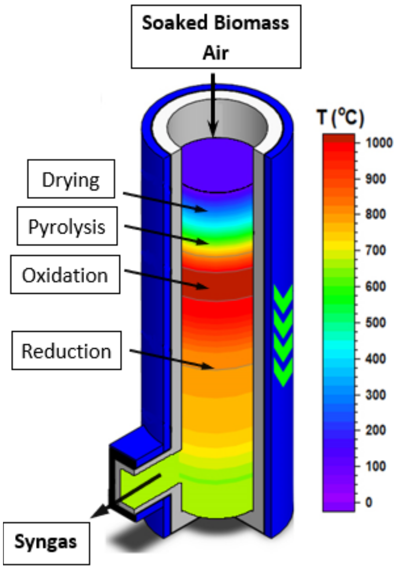

Fig. 1. Stages of thermochemical process in open downdraft gasifier biomass gasification [29]

2.1.2. System thermal efficiency

System performance can be evaluated using a thermal efficiency approach. Biomass gasification systems utilizing steam typically achieve efficiencies below 20%, while motor engines or gas turbines operate within an efficiency range of 20–45% [30]. The thermal efficiency of the system was determined using Equation (1) [31–33]:

$$\eta_{sys} = \frac{\dot{Q}_{syn}}{\dot{Q}_{bio}} \tag{1}$$

The syngas heat rate ($\dot{Q}_{syn}$) was determined using Equation (2) [31,33], where $\dot{m}_w$ represents the mass flow rate of water evaporated by steam boiler, h_g is enthalpy of steam (2676.1 kJ/kg at 100 °C and 1 atm), and h_f is the enthalpy of liquid water (519.04 kJ/kg at 100 °C and 1 atm) [31–33].

$$\dot{Q}_{syn} = \dot{m}_{steam}(h_g - h_f) \tag{2}$$

The heat rate from the biomass feed ($\dot{Q}_{bio}$) was determined using Equation (3) [32], where $\dot{m}_{bio}$ represents the biomass feed rate, and LHV denotes the lower heating value (calorific value) of corn cob, which is (14.6 MJ/kg) [34].

$$\dot{Q}_{bio} = \dot{m}_{bio}\, LHV \tag{3}$$

2.2. Properties of Corn Cob Biomass

The biomass used in this study consisted of corn cobs obtained from an agricultural area near the research facility in Subang, West Java. Corn cobs account for approximately 30% of the total weight of harvested corn [5]. The net heating value (LHV) of corn cobs ranges from 14 to 16

MJ/kg of dry matter [34,35]. Proximate analysis of corn cobs showed 71.38% volatile matter, 6.51% ash, and 12.11% fixed carbon based on 10% dry mass. Meanwhile, ultimate analysis indicated that corn cobs contain 44.78% carbon, 6.02% hydrogen, and 0.22% nitrogen, also based on 10% dry mass [36]. Corn cobs exhibit hygroscopic properties, allowing them to absorb large amounts of water, and have a density of 282.38 kg/m^3 [37].

As shown in Fig. 2, the corn cobs used in this study were pretreated by soaking in water before being fed into the gasifier. The selected corn cobs measured 2–5 cm in length and 2–4 cm in diameter.

(a) **(b)**

Fig. 2. **(a)** Shape and size of the corn cob, **(b)** Soaked corn cobs

2.3. Experimental Methods

The research was conducted at the Gasification Laboratory of the Department of Mechanical Engineering, Faculty of Engineering, University of Subang. Fig. 3 presents a schematic diagram of the gasification system. The experimental setup included a reactor, cyclone separators, a heat exchanger, and a steam boiler.

The reactor temperature was measured during the process using five temperature sensors: one K-type thermocouple and four S-type thermocouples. The K-type thermocouple, housed in a steel casing (T0), was positioned at the top of the reactor. The S-type thermocouples, housed in ceramic casings, were positioned below T0 at 20 cm intervals. Designated as T1, T2, T3, and T4, these thermocouples provided essential data for monitoring the gasification process within the reactor. The placement of sensors at different heights enables accurate tracking of temperature variations throughout the reactor. Real-time data logging, facilitated by the Lutron TM-9747SD and Lutron BTM-420SD data loggers, allows for rapid analysis and adjustment of gasifier parameters (Fig. 4.a). The thermal power of the syngas was determined through combustion in the flare. The resulting flame heated a water container (boiler), where the amount of water evaporated was directly correlated with the thermal power of the syngas produced by the gasifier (Fig. 4.b). The boiler was connected to an FTU DLM01 data logger, which measured and recorded its weight.

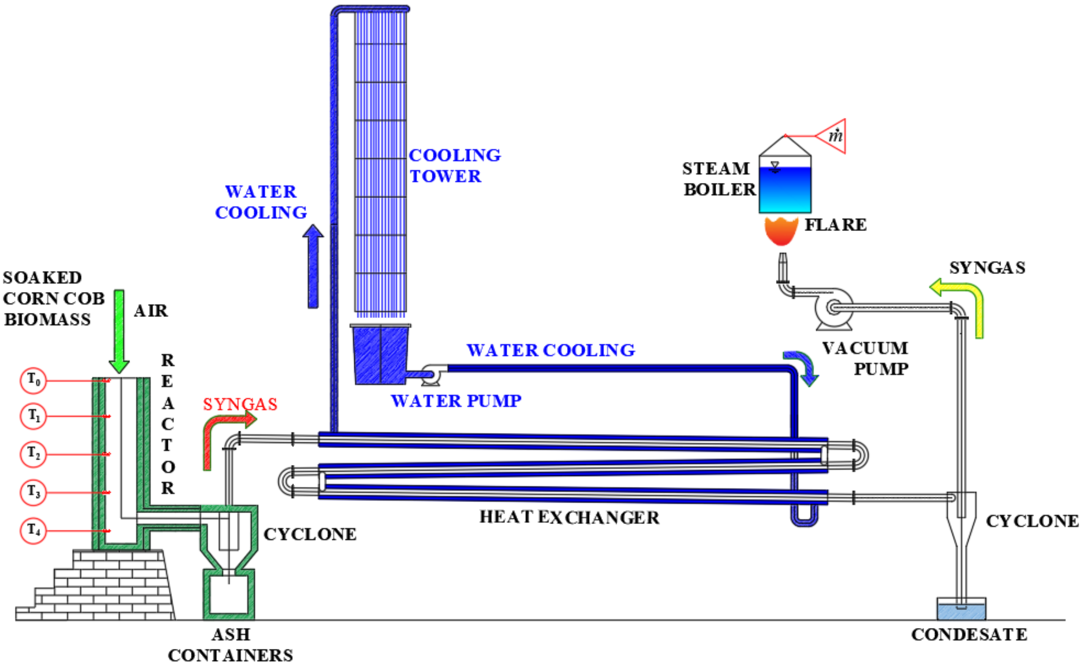

Fig. 3. Schematic diagram of biomass gasification system using open downdraft gasifier.

(a) **(b)**

Fig. 4. (a) Reactor and temperature measurement device, **(b)** Boiler.

The experimental protocol was as follows: First, charcoal was added to the gasifier. The cooling system and suction pump were then activated, and the uppermost charcoal was ignited to preheat the system. A small torch was placed on the flare to initiate combustion and prevent the escape of carbon monoxide gas. The steam boiler, along with its monitoring and recording equipment, was positioned in the flare. All data loggers recorded data continuously. When the gasifier temperature approached 1,000 °C, soaked corn cobs were introduced into the gasifier.

3. Results and Discussion

3.1. Gasification Temperature Profile

Fig. 5. Gasifier temperature profile illustrates the reactor temperature during the corn cob experiment, ranging from 1,064 to 614°C, with a dominant temperature of 892°C. At the start of

the experiment, the oxidation zone temperature was 1,027°C at a position of 20 cm. Over time, the oxidation zone shifted downward reaching 60 cm with a reduced temperature at the 48th minute. The temperature of the corn cob gasification process declined to 614°C by the end of the experiment. This drop below 700°C hindered the gasification process from reaching its maximum potential, as the reduction process ceased when temperatures fell below this threshold [25–27]. The minimal or absent gasification zone at the end of the experiment contributed to a weak and incomplete reduction process, indicating suboptimal gasification effectiveness [25,28]. Maintaining temperatures above 800°C is crucial for a successful gasification process, as deviations from this threshold can result in failure.

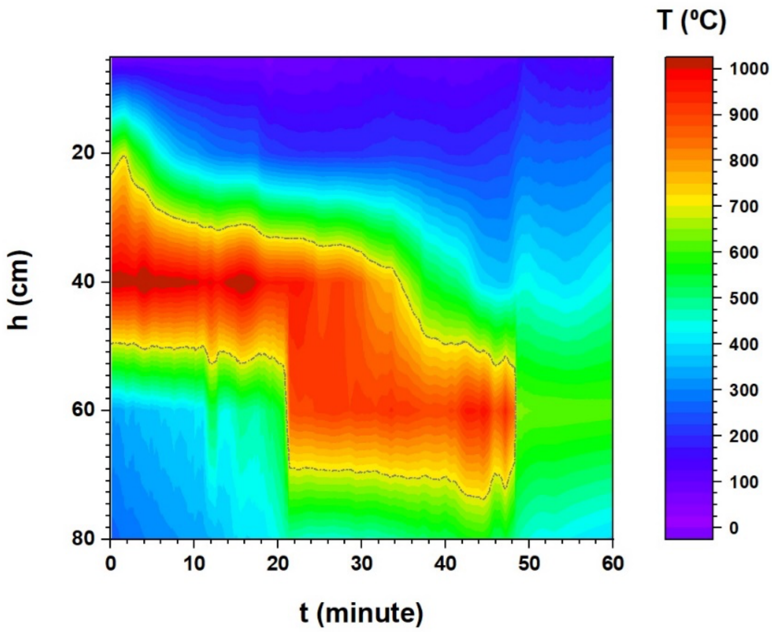

Fig. 5. Gasifier temperature profile

Traditional gasification processes require a pre-treatment stage to dry the biomass feedstock. Downdraft fixed-bed gasifiers operate inefficiently when the biomass moisture content exceeds 20% [29]. The development of gasifiers capable of handling higher moisture content remains limited to a maximum of 30% [30,31]. A higher moisture content does not necessarily improve the process. Excess water absorbs significant heat during evaporation, causing temperature fluctuations within the reactor. Additionally, excessive water vapor hinders gasification reactions, leading to lower gas yields and diminished syngas quality [32]. As shown in Table 1, the moisture test of quenched corn cobs revealed a moisture content of 56.78%. Since soaked corn cobs exceed 30% moisture, they lead to gasification failure [30,31].

3.2. Water Content of Soaked Corn Cob

The moisture content of soaked corn cobs was determined by weighing them in a cup of known mass. The initial mass was recorded before immersion in water. The samples were soaked for 15 minutes and drained for 5 minutes before reweighing. The corn cobs were weighed and then placed in an oven at a temperature of 104°C to 110°C for 16 hours. The mass remained constant, with a minimal change of 0.2% [33].The moisture content was calculated using the following equation:

$$\text{Moisture in analysis sample, } \% = \frac{(m_i - m_f)}{(m_i - m_c)} x100\%$$

where: m_i= initial weight (gram), m_f= final weight (gram) and container weight (gram).

The moisture measurement results for dried and soaked corn cobs are presented in Table 1.

Table 1. Moisture value of dried and soaked maize cobs

Sample number	Dry condition	Soaked condition
Sample 1	10.39	62.36
Sample 2	10.15	59.37
Sample 3	10.22	54.94
Sample 4	11.33	56.81
Sample 5	11.18	51.25
Sample 6	11.36	55.95
Sample 7	10.48	56.25
Sample 8	10.63	57.83
Sample 9	11.04	56.31
Average	**10.75**	**56.78**
Standard deviation	**± 0.45**	**± 2.87**

3.3. Evaporation Rate of Water in The Steam Boiler

Fig. 6 shows the quantity of water evaporated due to heat supplied by syngas combustion on the flare. For approximately 48 minutes, the data closely follow the quadratic trendline, Y = $0.456X^2 + 26.816X$ with $R^2 = 0.999$. As illustrated in Fig. 6, water evaporation is directly proportional to the heat supplied by syngas combustion. The heating process begins with the flame from the syngas combustion, initially raising the water temperature within the boiler until it reaches its boiling point. During this phase, the temperature increases without a corresponding phase change. Once the boiling point is reached, the water begins to convert into steam. Notably, at this stage, the supplied heat energy does not raise the temperature, but instead is used for the phase transition from water to steam (i.e., latent heat of evaporation) [34,35]. As syngas production increases, heat generation also rises, leading to greater amounts of water vapor produced in the boiler.

As demonstrated in Fig. 6, the slope of the line increases sharply, indicating an increase in the production of water vapor. However, the process is limited to 48 minutes, after which no further evaporation occurs. Optimal results are attained at humidity levels below 30%. Li et al. [32]. suggest that biomass moisture facilitates the gasification process but only up to a limited extent (30% moisture). However, higher moisture levels are not necessarily advantageous. Excess water can absorb significant heat during evaporation, reducing the efficiency of the gasification reaction.

Consequently, this can lower gas yield and diminish syngas quality, particularly when moisture levels exceed 30% (56.78%) [32].

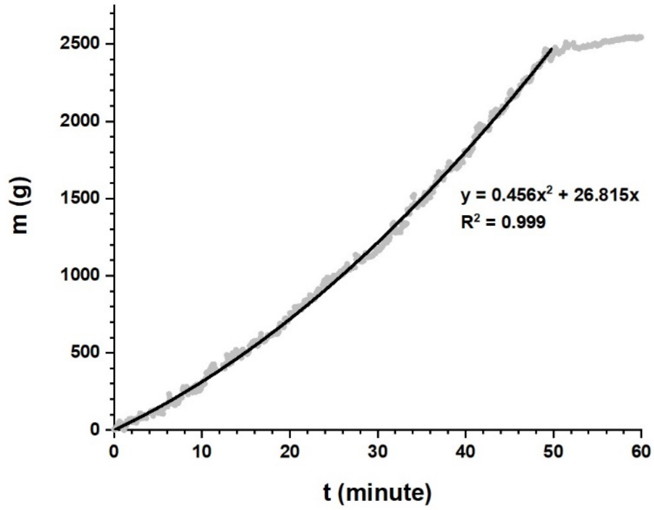

Fig. 6. Evaporation rate in the steam boiler

3.4. Thermal Performance of The System

The performance of this gasification system was assessed by observing the energy input of corn cob biomass and the energy output of syngas combustion, which was utilized to evaporate water in the steam boiler. A total of 2,337 g of water evaporated for 48 minutes, resulting in an average evaporation rate of 48.69 g/minute. This is expressed as $\dot{m}_{steam}$ = 0.00081146 kg/s. The syngas heating power is calculated using Equation (2) as follows:

$$\dot{Q}_{syn} = \dot{m}_{steam}\,(h_g - h_f)$$
$$= 0.00081146 \text{ kg/s. } (2{,}676.1 \text{ kJ/kg} - 519.04 \text{ kJ/kg})$$
$$= 1.76 \text{ kW}$$

The dry weight of corn cobs fed into the gasifier over 48 minutes was 4,480 g, resulting in an average feed rate of 93.33 g/minute. This is expressed as $\dot{m}_{bio}$ = 0,00168 kg/s. The heating power derived from biomass is calculated using Equation (3) as follows:

$$\dot{Q}_{\text{bio}} = \dot{m}_{bio} \,.\, \text{LHV}$$
$$= 0.00168\ kg/s \,.\, 14{,}644\ kJ/kg$$
$$= 24.61\ kW$$

System performance is evaluated based on thermal efficiency, calculated using Equation (1) as follows:

$$\eta_{sys} = \frac{\dot{Q}_{syn}}{\dot{Q}_{\text{bio}}}$$
$$= \frac{1.76\ kW}{24.61\ kW}$$
$$= 7.14\%$$

Soaked corn cobs were successfully utilized as a gasification feedstock in an open downdraft gasifier for a 48-minutes runtime. Heat-producing and heat-absorbing chemical reactions remained balanced, maintaining a high temperature zone in the gasifier and sustained syngas production, as shown in Fig. 5. The syngas burned with a stable flame at the flare. During this period, steam boiler evaporation data indicated an average thermal power of 1.76 kW with an efficiency of 7.14%. This efficiency remains below the standard of a steam boiler, which typically ranges from 10 to 20% [34,35].

An abrupt change occurred at the 48th minute of operation. The high-temperature zone in the gasifier suddenly disappeared, preventing effective gasification. Consequently, the flame at the flare became unstable. At this point, steam boiler evaporation data showed a trend change. As demonstrated in Fig. 6, the evaporated water data became discontinuous, indicating an absence of heat supply to the boiler and the cessation of gasification. The sudden change in the gasifier temperature profile at the 48th minute suggests a physical alteration in the gasifier bed. The rapid reduction of corn cob charcoal to gas creates a void in the solid material, causing a sudden decline in the biomass level within the reactor. This, in turn, lowers the gasification zone. The subsequent collapse of this void disrupts the biomass layer within the gasifier. Soaked corn cobs then enter the heat-generating zone, extinguishing it, thereby leading to insufficient heat to sustain the endothermic gasification process. Corn cob may enter the center of the heat-generating zone and extinguish it, preventing adequate heat generation to sustain endothermic gasification processes.

At the 21st minute of operation, another cave-in occurred, but with a different outcome than the one at 48th minute. This expanded the high-temperature zone in the gasifier, as shown in Fig. 5, enhancing the gasification process by providing a hotter, more reactive biomass bed. However, no significant change was observed in the evaporation data. The investigation into the utilization of soaked palm kernel shells, combined with modification to the suction pump motor, yielded favorable outcomes, particularly in improving gasification temperature performance and water evaporation process within the boiler [36].

4. Conclusions

Corn cob gasification experiments using the soaked treatment resulted in an ineffective gasification process due to the high moisture content (56.78%), which exceeded the maximum threshold of 30%. Excess moisture significantly reduced the temperature and the high-temperature zone. This phenomenon is evident in the gasification temperature profile, which dropped from 1024°C to 614°C. Since effective gasification typically requires temperatures above 700°C, this decline led to a corresponding reduction in the gasification zone. The syngas produced was burnt to generate steam, achieving a thermal efficiency of 7.14%. However, after 48 minutes of operation, steam generation ceased due to a drop in gasifier temperature, halting the gasification process. Further research is needed to determine the optimal conditions for gasification of corn cobs, as the wet corn cob experiment did not sustain the process. Exploring different treatment methods, such as using dry corn cobs or a combination of dry and wet, may improve the effectiveness and efficiency of the gasification process.

Abbreviations

Not applicable.

Data availability statement

Data supporting this study will be made available on request.

CRediT authorship contribution statement

Muhtar Kosim: Conceptualization, Methodology, Conceptual, Software, Validation, Writing and Editing, Visualization, Software. Kasda: Supervision, Validation, Writing-Reviewing. **Dede Iman Saputra**: Supervision, Visualization, Project administration. **Yuda Kurnia**: Data Curation, Writing - Original Draft, Resources. **Novandri Tri Setioputro**: Methodology, Conceptual, Formal analysis, Validation, Writing and Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Kementrian ESDM, Wahyu Kencono A, Dwinugroho M, Satra Baruna E, Ajiwihanto N. Handbook Of Energy & Economic Statistics Of Indonesia 2023. Ministry of Energy and Mineral Resources Republic of Indonesia; 2023. https://www.esdm.go.id/assets/media/content/content-handbook-of-energy-and-economic-statistics-of-indonesia-2023.pdf

[2] IESR. Indonesia Energy Transition Outlook 2024 IESR Institute for Essential Services Reform. Indonesia Energy Transition Outlook 2024, vol. 4:2024, 2023, p. 26–26. www.iesr.or.id

[3] Gioietta Kuo. When Fossil Fuels Run Out, What Then? Millennium Alliance for Humanity and the Biosphere (MAHB) 2019. https://mahb.stanford.edu/library-item/fossil-fuels-run/ (accessed September 29, 2021).

[4] Speight JG. Handbook of Gasification Technology. 2020. https://doi.org/10.1002/9781118773970.

[5] Cheng JJ. Biomass to Renewable Energy Processes. Second. CRC Press; 2017. https://books.google.co.id/books?hl=id&lr=&id=impQDwAAQBAJ&oi=fnd&pg=PP1&dq=Biomass+to+Renewable+Energy+Processes&ots=1DXtEV64u_&sig=kziD1avw0pSBD4RB0uNIHUi0Isw&redir_esc=y#v=onepage&q=Biomass to Renewable Energy Processes&f=false

[6] Kuang C. Analysis of Green House Gases and Positive Impact of Replacing Traditional Energy with Clean Energy. 2020 8th International Conference on Environment Pollution and Prevention (ICEPP 2020), E3S Web of Conferences 241, 02005 (2021); 2021, p. 5. https://doi.org/10.1051/e3sconf/202124102005.

[7] Soeder DJ, Borglum SJ. The Fossil Fuel Revolution: Shale Gas and Tight Oil. Cambrige, United State: Elsevier; 2019.

[8] Yang Z, Wei J, Ge Q. Friction or cooperation? Boosting the global economy and fighting climate change in the post-pandemic era. Humanities and Social Sciences Communications 2023;10:1–11. https://doi.org/10.1057/s41599-023-02307-4.

[9] Larch M, Wanner J. The consequences of non-participation in the Paris Agreement. European Economic Review 2024;163:104699. https://doi.org/10.1016/j.euroecorev.2024.104699.

[10] Tran HM, Tsai FJ, Lee YL, Chang JH, Chang L Te, Chang TY, et al. The impact of air pollution on respiratory diseases in an era of climate change: A review of the current evidence. Science of the Total Environment 2023;898:166340. https://doi.org/10.1016/j.scitotenv.2023.166340.

[11] Chishti MZ, Xia X, Dogan E. Understanding the effects of artificial intelligence on energy transition: The moderating role of Paris Agreement. Energy Economics 2024;131:107388. https://doi.org/10.1016/j.eneco.2024.107388.

[12] Sinsel SR, Riemke RL, Hoffmann VH. Challenges and solution technologies for the integration of variable renewable energy sources d a review. Renewable Energy 2020;145:2271–85. https://doi.org/10.1016/j.renene.2019.06.147.

[13] Eling J, Okot DK, Menya E, Atim MR. Densification of raw and torrefied biomass: A review. Biomass and Bioenergy 2024;184:107210. https://doi.org/10.1016/j.biombioe.2024.107210.

[14] Motta IL, Marchesan AN, Maciel Filho R, Wolf Maciel MR. Correlating biomass properties, gasification performance, and syngas applications of Brazilian feedstocks via simulation and multivariate analysis. Industrial Crops and Products 2022;181:114808. https://doi.org/10.1016/j.indcrop.2022.114808.

[15] Makul N, Fediuk R, Amran M, Al-Akwaa MS, Pralat K, Nemova D, et al. Utilization of biomass to ash: An overview of the potential resources for alternative energy. Materials 2021;14:1–20. https://doi.org/10.3390/ma14216482.

[16] Tri Setioputro N, Kosim M, Kasda, Sukwadi R, Basuki WW, Saputra DI. Investigation of reactor temperature and performance of syngas cooling system for vacuum gasification of soaked biomass. Case Studies in Thermal Engineering 2023;50. https://doi.org/10.1016/j.csite.2023.103430.

[17] Ahmad W, Nisar J, Anwar F, Muhammad F. Bioresource Technology Reports Future prospects of biomass waste as renewable source of energy in Pakistan : A mini review.

Bioresource Technology Reports 2023;24:101658. https://doi.org/10.1016/j.biteb.2023.101658.

[18] Primadita DS, Kumara .N.S., Ariastina WG. A Riview on Biomass For Electricity Generation In Indonesia. Journal of Electrical, Electronics and Informatics, 2020;4:1–9. https://www.researchgate.net/profile/I-Nyoman-Satya-Kumara-2/publication/342739788_A_Review_on_Biomass_For_Electricity_Generation_In_Indonesia/links/5f0467ff92851c52d61de45f/A-Review-on-Biomass-For-Electricity-Generation-In-Indonesia.pdf

[19] Purohit P, Tripathi AK, Kandpal TC. Energetics of coal substitution by briquettes of agricultural residues. Energy 2006;31:1321–31. https://doi.org/10.1016/j.energy.2005.06.004.

[20] Badan Pusat Statistik. Luas Panen dan Produksi Jagung di Indonesia 2023. BPS - Statistics Indonesia 2023. https://www.bps.go.id/id/pressrelease/2023/10/16/2049/luas-panen-dan-produksi-jagung-di-indonesia-2023--angka-sementara-.html.

[21] Nadaleti WC, Przybyla G. SI engine assessment using biogas, natural gas and syngas with different content of hydrogen for application in Brazilian rice industries: Efficiency and pollutant emissions. Int J Hydrogen Energy 2018;43:10141–54. https://doi.org/10.1016/j.ijhydene.2018.04.073.

[22] Song G, Zhao S, Wang X, Cui X, Wang H, Xiao J. An efficient biomass and renewable power-to-gas process integrating electrical heating gasification. Case Studies in Thermal Engineering 2022;30:101735. https://doi.org/10.1016/j.csite.2021.101735.

[23] Widiasri NLP, Husni A, Sutrisna R, Liman L. Pengaruh Dosis Ragi Tempe Pada Pembuatan Tempe Tongkol Jagung Terhadap Kandungan Nutrisi Untuk Pakan Ternak. Jurnal Riset Dan Inovasi Peternakan (Journal of Research and Innovation of Animals) 2024;8:100–6. https://doi.org/10.23960/jrip.2024.8.1.100-106.

[24] Usman U, Beni S, Atlantika YN, Hapsari VR, Vuspitasari BK. PEMANFAATAN LIMBAH TONGKOL JAGUNG MENJADI BRIKET BAHAN BAKAR YANG RAMAH LINGKUNGAN DAN BERNILAI JUAL. SELAPARANG: Jurnal Pengabdian Masyarakat Berkemajuan 2023;7:2808–14. https://doi.org/doi.org/10.31764/jpmb.v7i4.19777.

[25] Carmona OM, Vederza A, Morales R AD, Lenis YA. Steady and transient state behavior of a gasification process under fixed-bed downdraft configuration. Heliyon 2024;10. https://doi.org/10.1016/j.heliyon.2024.e34781.

[26] Molino A, Chianese S, Musmarra D. Biomass Gasification Technology: The State Of The Art Overview. Journal of Energy Chemistry 2016;25:10–25. https://doi.org/10.1016/j.jechem.2015.11.005

[27] Motta IL, Miranda NT, Maciel Filho R, Wolf Maciel MR. Biomass gasification in fluidized beds: A review of biomass moisture content and operating pressure effects. Renewable and Sustainable Energy Reviews 2018;94:998–1023. https://doi.org/10.1016/j.rser.2018.06.042.

[28] Diyoke C, Gao N, Aneke M, Wang M, Wu C. Modelling of down-draft gasification of biomass – An integrated pyrolysis, combustion and reduction process. Applied Thermal Engineering 2018;142:444–56. https://doi.org/10.1016/j.applthermaleng.2018.06.079.

[29] Arjharn W, Hinsui T, Liplap P, Raghavan GS. Evaluation of electricity production from different biomass feedstocks using a pilot-scale downdraft gasifier. Journal of Biobased Materials and Bioenergy 2012;6:309–18. https://doi.org/https://doi.org/10.1166/jbmb.2012.1213.

[30] Cummer KR, Brown RC. Ancillary equipment for biomass gasification. Biomass and Bioenergy 2002;23:113–28. https://doi.org/doi.org/10.1016/S0961-9534(02)00038-7.

[31] Hughes WEM, Larson ED. Effect of fuel moisture content on biomass-IGCC performance 1998. https://doi.org/https://doi.org/10.1016/j.fuel.2006.05.025.

[32] Li Z, Li J, Yu T, Jia X, Zhao J, Yan B, et al. Chemical looping gasification of high-moisture content biomass: The interactions between H2O and oxygen carrier. Applied Energy 2024;368:123529. https://doi.org/10.1016/j.apenergy.2024.123529.

[33] E871-82 A. Standard Test Method for Moisture Analysis of Particulate Wood Fuels 1. Annual Book of ASTM Standards 2014;82:2. https://doi.org/10.1520/E0871-82R13.2.

[34] Martinez-Boggio SD, Merola SS, Teixeira Lacava P, Irimescu A, Curto-Risso PL. Effect of fuel and air dilution on syngas combustion in an optical SI engine. Energies 2019;12. https://doi.org/10.3390/en12081566.

[35] Prins MJ, Ptasinski KJ, Janssen FJJG. From coal to biomass gasification: Comparison of thermodynamic efficiency. Energy 2007;32:1248–59. https://doi.org/10.1016/j.energy.2006.07.017.

[36] Setioputro NT, Kosim M, Kosasih DP, Sukwadi R, Basuki WW, Saputra DI. Effectiveness Study on The Vacuum Biomass Gasification System Using Variation of Suction Pump Rotation Power and Biomass Wetness. WSEAS Transactions on Earth Sciences and Human Constructions 2022;2:72–80. https://doi.org/10.37394/232024.2022.2.11.