
DETERMINATION OF OPTIMUM EQUIVALENT RATIO AND FEED RATE FROM GASIFIER WITH SEVERAL TYPES OF BIOMASS

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ABSTRACT

This study aims to create a CFD model aligned with lab test results from previous studies, conduct simulation tests using several types of biomass as input and optimize the operating parameters of various types of biomass to produce optimum syngas. The method used in this research is literature study and modelling using Ansys Fluent software. The results of this study indicate that biomass is a source of new and renewable energy (EBT) which has abundant potential in Indonesia, but its use could be more optimal. Biomass gasification is one of the most promising techniques used to convert solid fuels into useful gaseous fuels, which can be widely used in many households and industrial applications such as power generation and internal combustion engines. This research implies that it can help determine the optimum equivalence ratio and feed rate for a gasifier that utilizes various types of biomass. By finding the optimal combination, the composting process can achieve higher energy efficiency, resulting in more energy being generated from the biomass used. Additionally, by knowing the appropriate equivalence ratio and feed rate, this research can assist in optimizing the biomass composting process in the gasifier.

Keywords: biomass, syngas gasifier.

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INTRODUCTION

Reducing emissions to mitigate the negative impacts of climate change has become a common goal of the international community in recent years, with more and more countries and businesses worldwide committing to net zero emissions, mostly by mid-century (Lukmadi & Sitabuana, 2022). The race toward carbon neutrality or climate neutrality has coincided with worsening extreme weather events, lowering the cost of renewable energy, and increasing awareness of climate change.

Biomass is considered a renewable energy source that is clean and environmentally friendly and can be a good alternative to fossil fuels (Reddy et al., 2023). Biomass with appropriate process options can be converted into solid, liquid and gaseous fuels that can be used for energy production. Therefore, research has worked on various techniques for increasing biomass energy production (Vassilev et al., 2015).

Biomass is a new and renewable energy source (EBT) with abundant potential in Indonesia. However, its use has yet to be optimal. Biomass used as an energy source (fuel) in Indonesia generally has low economic value or is a waste that has taken its primary product. The biomass can come from plants, trees, grass, sweet potatoes, agricultural waste, forest waste, faeces and livestock manure (Parinduri & Parinduri, 2020). The potential for biomass resources in Indonesia is estimated at 49,810 MW from plants and waste (Ardilasari, 2023). The great potential of existing biomass for energy today is plantation waste, such as oil palm, coconut and sugarcane, as well as forest product

waste, such as sawn waste and wood production waste. (Kasmaniar et al., 2023). Food crop waste (agriculture) also has a large amount. However, most of it has been used by the community for various purposes (agriculture, energy, industry). Several companies export plantation waste, such as palm kernel shells, coconut cake, and molasses from sugarcane.

Meanwhile, plants containing starch and sugar are still used for food. Several large industries have been able to create electrical energy from waste biomass and use it for company operations. At the same time, many small, medium and large companies have also carried out the form of direct energy (direct combustion). Fuel production includes vegetable oil from food crops but has yet to be produced on a large scale. Kemiri Sunan, sampling, *Jatropha curcas*, water hyacinth, and algae are planted with a high potential for energy because they do not come into contact with food. However, they have yet to be produced on a mass scale. Animal husbandry waste in several cities/regencies has been used as household-scale biogas.

In contrast, municipal waste has been used as a raw material for electricity in Jakarta and Denpasar. The availability of biomass has been concentrated geographically, but its utilization could have been better. Existing energy policies and regulations, such as permits and energy prices, still need to support the optimal use of biomass as a raw material for renewable energy.

Concerning the production process biomass gasification is one of the most promising techniques used to convert solid fuels into useful gaseous fuels, which can be widely used in many households and industrial applications such as power generation and internal combustion engines. (Pah, 2022). The most common use of biomass for energy is direct combustion, followed by gasification, carbonization and pyrolysis (Basu, 2018).

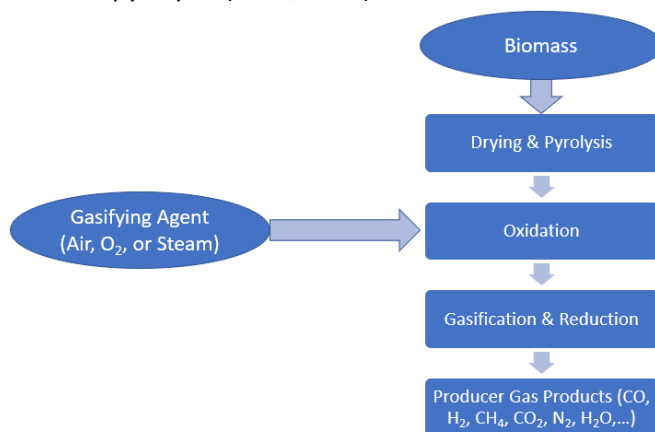


Figure 1. Biomass Gasification

Biomass gasification is increasing significantly in terms of industrial and market applications for several reasons (Bridgwater et al., 2022) :

1. It is a renewable energy source.
2. It can be used as a good alternative for electricity production or to reduce electricity consumption during peak load times.
3. Good sewage system.
4. It can be used in CHP applications.

In addition, gasification also has several advantages compared to other techniques (e.g. pyrolysis and combustion), as follows:

1. The gasification products can be used directly in internal combustion engines and gas turbines, making gasification more important than other technologies.
2. Negligible emissions compared to direct combustion.
3. Wide range of applications, such as heat, electricity, steam, and chemicals.
4. The resulting gas product is of high value in terms of syngas composition.

Gasification is a thermochemical process that converts solid fuel into gaseous fuel at temperatures between (700-900)°C (Basu, 2018). Gasification produces carbon monoxide, hydrogen and small amounts of methane as desired products with other unwanted gases such as nitrogen, carbon dioxide and other hydrocarbons. In gasification, organic volatiles do not condense rapidly, so they are usually carried away with the product gas, forming a viscous substance called tar. Both tar and char are undesirable for any downstream application, e.g. when using producer gas in internal combustion engines and gas turbines (Basu, 2018). Tar separation is a major challenge for using the resulting syngas as it will condense and cause blockages in the engine and valves.

Biomass refers to organic matter derived from plants or animals (Simorangkir & Syaiful, nd) that are alive or lived in the past. Universally accepted definitions take much work to find. However, one used by the United Nations Framework Convention on Climate Change (UNFCCC) is relevant here:

Non-fossilized and biodegradable organic materials derived from plants, animals and microorganisms. It should also include products, by-products, residues and wastes from agriculture, forestry and related industries, and the nonfossil and biodegradable organic fractions of industrial and municipal wastes.

Biomass also includes gases and liquids from decomposing non-fossilized and biodegradable organic matter (Basu, 2013). As a sustainable and renewable energy source, biomass is continuously formed by the interactions of CO₂, air, water, soil and sunlight with plants and animals. After the organism dies, the microorganisms break down the biomass into its constituent parts, such as H₂O, CO₂, and their potential energy. Carbon dioxide, released by biomass through the action of microorganisms or combustion, was absorbed by it in the past, so burning biomass does not add to the Earth's total CO₂ stock. Therefore it is called greenhouse gas neutral or GHG neutral.

A fluidized bed gasifier offers uniform temperature distribution and a good mixing platform for gas and solid. That, in turn, reduces the risk of fuel stack agglomeration (Thomson et al., 2020). Silica, sand, dolomite, and glass beads are commonly used as bed materials for fluidized bed gasifiers. However, it was reported that magnesite could further increase H₂ production compared to sand as a coating material (Morris et al., 2018). The operating temperature of a fluidized bed reactor is highly dependent on the melting point of the lining material and ash. Hence, it is limited to 923 to 1223 K (Warnecke, 2020). The pressure ranges from 0 to 70 bar (Pang, 2016). Tar formation is intermediate between the updraft and downdraft gasifiers, with an average of 10 g/N.m³ (Basu, 2018). Due to the temperature at which these gasifiers operate, the reaction cannot move closer to equilibrium, reducing the formation of hydrocarbons at the gas outlet [18]. In contrast, the carbon conversion efficiency of these gasifiers is significant and can reach 95% (Chhiti & Kemiha, 2013).

Bubbling bed gasifier is classified as the oldest reactor in fluidized bed gasifier (Wheeldon & Thimsen, 2013). Bedding is mostly made of inert particles such as sand or silica. Moreover, it was observed that catalytic activity in the base material significantly increased the tar conversion rate

(Wheeldon & Thimsen, 2013). In these reactors, the gasification medium rises to the bed at a low gas velocity of $<1 \text{ ms}^{-1}$ to perform the fluidization process and maintain the state of the gas bubble mixture. The cross-sectional area increases when the particles reach the top of the bed. Hence, the velocity, in turn, decreases, causing the particles to descend the bed. Since this favours the formation of particulates, the reactor needs bubbling bed cyclone separators at the exit of the reactor (Gray, 2017).

This research has three objectives: 1. Create a CFD model aligned with the results of lab tests from previous studies 2. Conduct simulation tests using several types of biomass as input. 3. Optimizing the operating parameters of various types of biomass to produce optimum syngas.

METHODS

The research method used by the author to answer the objectives of the research is to use literature studies and modelling using Ansys Fluent software.

The flow chart of the study conducted by the author is as follows:

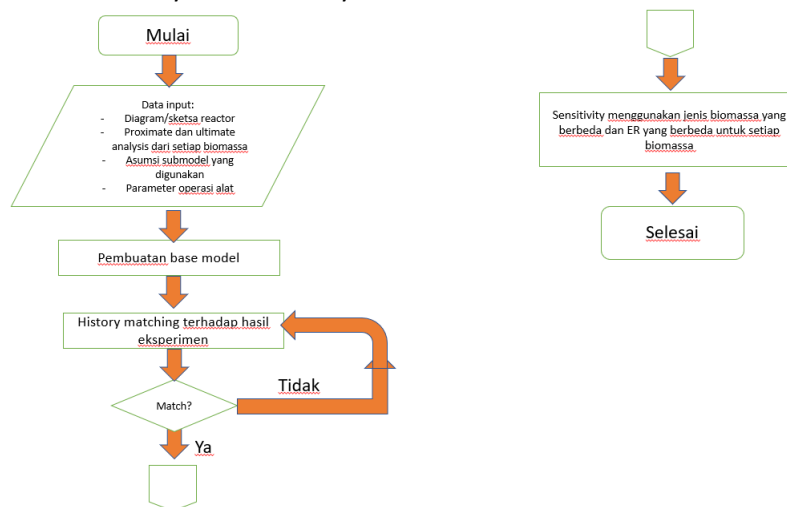


Figure 2. Research Flow Chart

For the modelling itself, the process from making the model to the sensitivity used for each type of biomass is as follows:

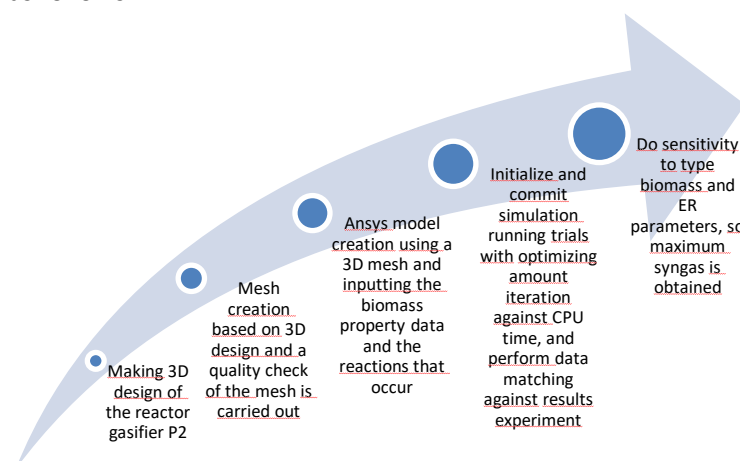


Figure 3. The Process From Model Creation to The Used Sensitivity.

In this study, the authors used several types of biomass as input in the simulation. Proximate data and ultimate analysis of these biomasses are needed as input data in Ansys Fluent. These data can be seen in the following table:

Table 1. Data Proximate and Ultimate Analysis of each type of biomass

Biomass	Proximate analysis (fraction)			Ultimate analysis (fraction)				
	volatile	Fixed Carbon	Ash	C	H	O	N	S
Rice husk	0.09	0.13	0.58	0.58	0.04	0.06	0.33	0
Corn cob	0.80	0.19	0.01	0.47	0.06	0.45	0.02	0.0001
Wheat Straw	0.71	0.20	0.09	0.43	0.05	0.39	0.12	0.0011
Sugarcane Bagasse	0.74	0.15	0.11	0.45	0.05	0.40	0.10	0.0001
Cotton Dregs	0.67	0.15	0.18	0.40	0.05	0.36	0.19	0

The chemical reaction equation used as a basis in Ansys Fluent is as follows (Murugan & Sekhar, 2017) :

Table 2. The reaction equations used in the simulation model

Reactions	Pre-exponential factor (sec ⁻¹)	The activation energy (J mol ⁻¹)	References
H ₂ O(l) - H ₂ O(v)	5.3 x 10 ¹⁰	88 x 10 ³	Franciso et al. (2008)
C+O ₂ - CO ₂	93.5 x 10 ³	82.8 x 10 ³	Fletcher et al. (2000)
2CO + O ₂ - 2CO ₂	10 x 10 ¹⁷	166.28 x 10 ³	Franciso et al. (2008)
CH ₄ + 1.5O ₂ - CO + 2H ₂ O	92 x 10 ⁵	80.23 x 10 ³	Franciso et al. (2008)
2H ₂ + O ₂ - 2H ₂ O	10 x 10 ¹¹	42 x 10 ³	Avdhesh (2008)
CH ₂ O - CO + H ₂	14 x 10 ⁷	179.50 x 10 ³	Fletcher et al. (2000)
C + CO ₂ - 2CO	34 x 10 ⁶	179.50 x 10 ³	Fletcher et al. (2000)
C + 2H ₂ - CH ₄	4.189 x 10 ⁻³	19.21 x 10 ³	Babu and Pratik (2006)
CH ₄ + H ₂ O - CO + 3H ₂	16.50 X 10 ¹⁰	33.90 x 10 ⁷	Luc et al. (2008)
CO + H ₂ O - CO ₂ + H ₂	2.824 X 10 ⁻²	32,840 X 10 ³	Ningbo and Aimin (2008)

RESULTS AND DISCUSSION

Design of 3D reactor gasifier P2 and mesh quality check

The 3D design of the reactor is made based on the initial design draft of the P2 mobile gasifier using Space claim. After the reactor design, meshing was carried out on the model by checking the mesh quality using orthogonal quality with an average of 0.76.

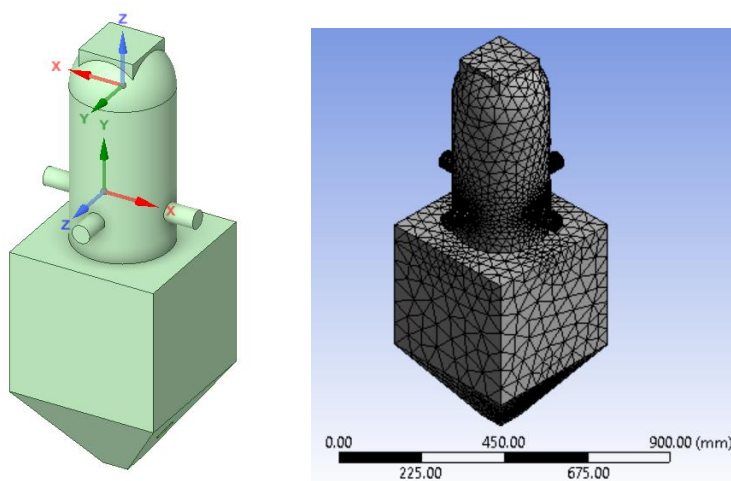


Figure 4. Schematic of the reactor included in the model and the mesh used

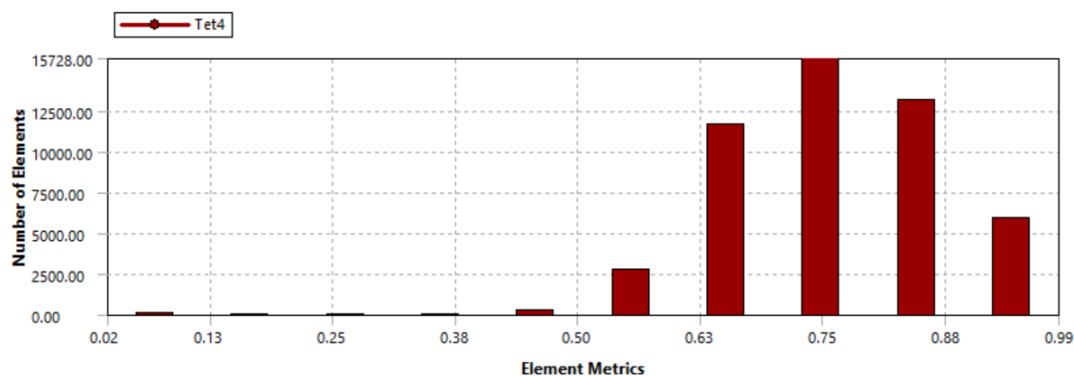


Figure 5. Mesh quality diagram

Making the Ansys fluent model

After meshing and checking the mesh quality, modelling in Ansys Fluent is continued by importing the mesh into the Ansys Fluent application, then inputting initial data in the form of biomass composition, elements involved, reactions that occur, boundary conditions, and settings other. A summary of the processes that occur in Ansys Fluent can be seen in the following table:

Table 3. Summary of processes and models used in Ansys Fluent

Process	Sub-models	Type
Model	turbulence	k-epsilon 2 equations
	Radiation	Discrete Ordinates
	Non-premixed Combustion	
Solution Method	Pressure-velocity coupling	coupled
	Momentum and Energy	2nd order upwind discretization scheme
	Pressure discretization scheme	PRESTO
Residual levels	10e-3 for all variables, for energy and radiation, 10e-6	

The next process is carried out after all the input data is entered to do the initial run to see the convergence of our created process. This is done by simulating with a high number of iterations. The author uses the initial number of iterations at 2000, then optimizes so that the number of iterations becomes 1000 iterations. Then initialization is carried out before the next simulation process is carried out. As input data, the feed rate and gas flow rate are used as follows:

Table 4. Feed rate and gas flow rate for each ER

Biomass		Air inlet ea (ER=0.15)	Air inlet ea (ER=0.27)	Air inlet ea (ER=0.4)	Air inlet ea (ER=0.6)
kg/hour	kg/s	kg/s	kg/s	kg/s	kg/s
5	0.001	0.0003	0.0005	0.0008	0.0012
12	0.003	0.0007	0.0013	0.0019	0.0028
15	0.004	0.0009	0.0016	0.0023	0.0035
20	0.006	0.0012	0.0021	0.0031	0.0047

Data matching

Data matching is carried out on the results of previous research based on the following table:

Table 5. Experimental results from previous research

ER	H2	CO	CH4	LHV
Experiment				
0.18	1.43%	3.73%	0.96%	0.97

ER	H ₂	CO	CH ₄	LHV
Experiment				
0.23	1.66%	4.64%	0.94%	1.1
0.27	3.34%	5.25%	0.87%	1.34
0.31	2.75%	5.24%	0.44%	1.11

After matching the data to ER 0.27 (the ER that produces the maximum syngas), the following results are obtained:

Table 6. Comparison of experimental results with simulations

Case	Results		
	H ₂ (%)	CO (%)	CH ₄ (%)
Experiment	3.34	5.25	0.87
Simulation	4.20	5.78	0.85

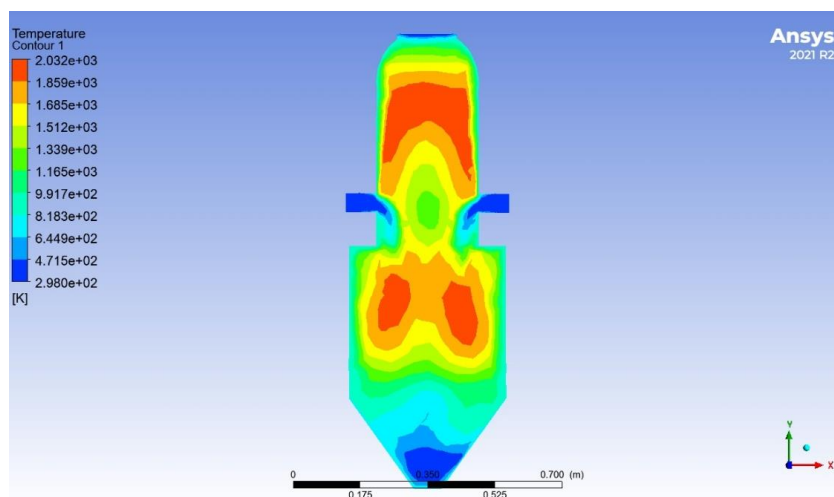


Figure 6. Rice husk temperature profile, ER 0.27, feed rate 12 kg/hour

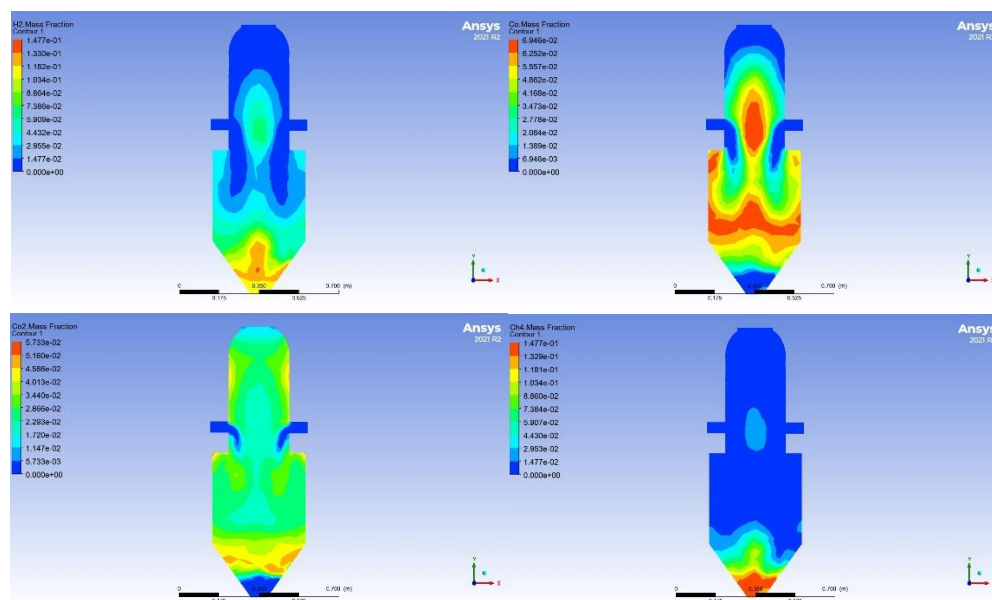


Figure 7. Profile H₂, CO, CO₂ and CH₄ of rice husk, ER 0.27, feed rate 12 kg/hour

Sensitivity

Sensitivity to several types of biomass was carried out by changing the proximate and ultimate analysis according to 849table 3: Data Proximate and Ultimate Analysis of each type of biomass. From the simulation results for several types of biomass, the following results are obtained:

Table 7. Simulation results of several types of biomass

Biomass	Result (ER = 0.27, Feed rate = 12 kg/hour)		
	H ₂ (%)	CO(%)	CH ₄ (%)
Rice Husk (Experiment)	3.34	5.25	0.87
Rice Husk (Simulation)	4.20	5.78	0.85
Corn cob	10.18	6.26	6.43
Wheat Straw	9.63	6.31	5.87
Sugarcane Bagasse	9.49	6.38	5.66
Cotton Dregs	9.41	6.39	5.55

The table shows that for conditions of equivalent ratio and the same biomass flow rate, corn cobs produce the most hydrogen, followed by wheat straw, bagasse and cotton waste. Carbon monoxide is produced by cotton dregs the most, followed by bagasse, wheat straw and corncobs. Methane is produced mostly by corn cobs, wheat straw, bagasse and cotton waste.

After that, sensitivity to ER was carried out for each type of biomass to see its effect on the resulting syngas output, and the results are as follows:

Table 8. Sensitivity to Equivalent Ratio

Biomass	Syngas Produced (H ₂ +CO+CH ₄) in an hour, kg			
	Feed rate 12 kg/hour			
	ER 0.15	ER 0.27	ER 0.40	ER 0.60
Rice Husk	0.62	1.30	1.15	0.76
Corn cob	1.21	2.74	2.41	1.91
Wheat Straw	1.12	2.62	2.33	1.77
Sugarcane Bagasse	1.16	2.58	2.28	1.83
Cotton Dregs	1.14	2.56	2.24	1.76

The table above shows that maximum syngas is produced at ER conditions of 0.27 with a biomass flow rate of 12 kg/hour for each biomass. Sensitivity to changes in the biomass flow rate was also carried out to see the effect of the biomass flow rate on the syngas produced with the following results:

Table 9. Sensitivity to biomass flow rate from Equivalent ratio 0.27

Biomass	Syngas Produced (H ₂ +CO+CH ₄) in an hour, kg			
	ER 0.27			
	Feedrate 5 kg/hour	Feedrate 12 kg/hour	Feedrate 15 kg/hour	Feedrate 20 kg/hour
Rice Husk	1.20	1.30	1.34	0.97
Corn cob	1.94	2.74	3.04	2.98
Wheat Straw	1.94	2.62	2.77	2.70
Sugarcane Bagasse	2.07	2.58	2.83	2.72
Cotton Dregs	1.93	2.56	2.75	2.67

Then for each biomass, a sensitivity to the biomass flow rate for ER 0.15, 0.27, 0.4, and 0.6 is carried out so that a feed rate vs ER surface chart can be made for each biomass, as follows:

Table 10. Sensitivity to Feed rate and ER for Rice Husk

Rice Husk	Syngas Produced (H ₂ +CO+CH ₄) in an hour, kg			
	ER 0.15	ER 0.27	ER 0.40	ER 0.60
Feedrate 5 kg/hour	0.56	1.20	0.99	0.83
Feedrate 12 kg/hour	0.62	1.30	1.15	0.76
Feedrate 15 kg/hour	0.61	1.34	0.96	0.58
Feedrate 20 kg/hour	0.60	0.97	0.70	0.35

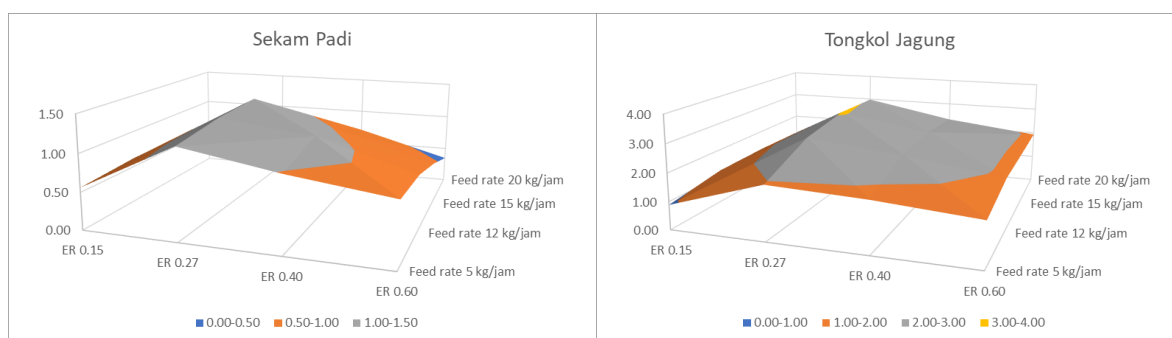


Figure 8. Surface chart of rice husks and corn cobs

Table 11. Sensitivity to Feed Rate and ER for Corn Cobs

Corncob	Syngas Produced (H ₂ +CO+CH ₄) in an hour, kg			
	ER 0.15	ER 0.27	ER 0.40	ER 0.60
Feedrate 5 kg/hour	0.89	1.94	1.81	1.57
Feedrate 12 kg/hour	1.21	2.74	2.41	1.91
Feedrate 15 kg/hour	1.26	3.04	2.48	1.91
Feedrate 20 kg/hour	1.23	2.98	2.33	1.93

Table 12. Sensitivity to Feed rate and ER for Wheat Straw

Wheat Straw	Syngas Produced (H ₂ +CO+CH ₄) in an hour, kg			
	ER 0.15	ER 0.27	ER 0.40	ER 0.60
Feedrate 5 kg/hour	0.84	1.94	1.67	1.52
Feedrate 12 kg/hour	1.12	2.62	2.33	1.77
Feedrate 15 kg/hour	1.20	2.77	2.33	1.88
Feedrate 20 kg/hour	1.27	2.70	2.33	1.73

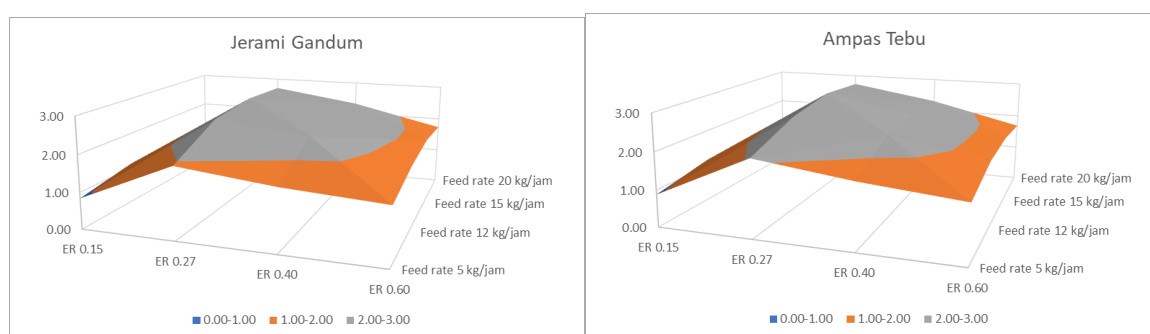


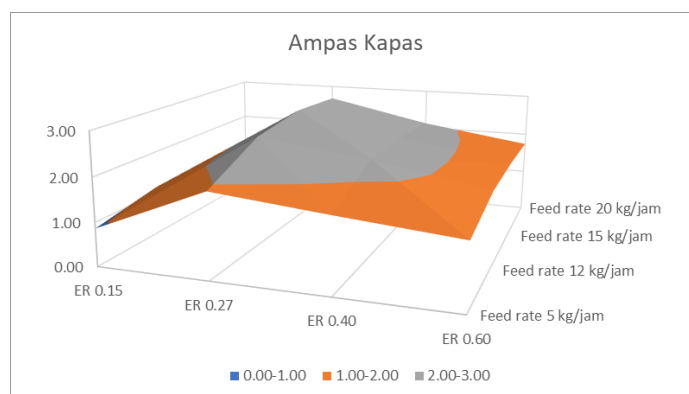
Figure 9. Surface chart of wheat straw and bagasse

Table 13. Sensitivity to Feed Rate and ER for Sugarcane Bagasse

Sugarcane Bagasse	Syngas Produced (H ₂ +CO+CH ₄) in an hour, kg			
	ER 0.15	ER 0.27	ER 0.40	ER 0.60
Feedrate 5 kg/hour	0.88	2.07	1.75	1.53
Feedrate 12 kg/hour	1.16	2.58	2.28	1.83
Feedrate 15 kg/hour	1.18	2.83	2.33	1.85
Feedrate 20 kg/hour	1.20	2.72	2.30	1.68

Table 14. Sensitivity to Feed rate and ER for Cotton Dregs

Cotton Dregs	Syngas Produced (H ₂ +CO+CH ₄) in an hour, kg			
	ER 0.15	ER 0.27	ER 0.40	ER 0.60
Feedrate 5 kg/hour	0.86	1.93	1.69	1.47
Feedrate 12 kg/hour	1.14	2.56	2.24	1.76
Feedrate 15 kg/hour	1.17	2.75	2.22	1.79
Feedrate 20 kg/hour	1.24	2.67	2.13	1.74

**Figure 10. Surface chart of cotton dregs**

In addition to sensitivity to ER and Feed Rate, it can also be seen the correlation between the oxygen content of each biomass and the syngas produced as follows:

Table 15. Correlation of oxygen content to the syngas produced

Biomass	Oxygen Content (mass fraction)	Syngas produced (kg/hour)
Rice Husk	0.06	1.30
Corn cob	0.45	2.74
Wheat Straw	0.39	2.62
Sugarcane Bagasse	0.40	2.58
Cotton Dregs	0.36	2.56

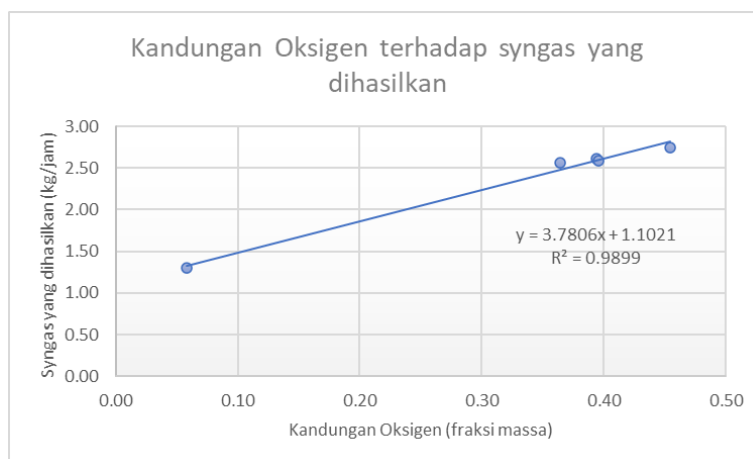


Figure 11. Graph of Oxygen Content vs Syngas produced

The graph shows that the more oxygen content in the biomass, the greater the total amount of syngas produced. This graph can be used for a P2 gasifier with an ER of 0.27 and a feed rate of 12 kg/hour. So when there are other types of biomass whose ultimate analysis is known, the syngas that will be produced can be predicted using this graph.

CONCLUSION

Biomass is a new and renewable energy source (EBT) with abundant potential in Indonesia. However, its use has yet to be optimal. Biomass gasification is one of the most promising techniques used to convert solid fuels into useful gaseous fuels, which can be widely used in many households and industrial applications such as power generation and internal combustion engines.

REFERENCES

- Ardilasari, L. A. (2023). *Pengaruh Perekat Daun Biduri (Calatropis gigantea) pada Briket Tongkol Jagung dengan Penambahan Plastik Low Density Polyethylene*. Politeknik Negeri Jember.
- Basu, P. (2013). *Chapter 3 - Biomass Characteristics* (P. B. T.-B. G. Basu Pyrolysis and Torrefaction (Second Edition) (ed.); pp. 47–86). Academic Press. <https://doi.org/https://doi.org/10.1016/B978-0-12-396488-5.00003-4>
- Basu, P. (2018). *Biomass gasification, pyrolysis and torrefaction: practical design and theory*. Academic press.
- Bridgwater, A. V, Toft, A. J., & Brammer, J. G. (2022). A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. *Renewable and Sustainable Energy Reviews*, 6(3), 181–246. [https://doi.org/10.1016/S1364-0321\(01\)00010-7](https://doi.org/10.1016/S1364-0321(01)00010-7)
- Chhiti, Y., & Kemiha, M. (2013). Thermal conversion of biomass, pyrolysis and gasification. *International Journal of Engineering and Science (IJES)*, 2(3), 75–85.
- Gray, D. (2017). Major gasifiers for IGCC systems. In *Integrated Gasification Combined Cycle (IGCC) Technologies* (pp. 305–355). Elsevier. <https://doi.org/10.1016/B978-0-08-100167-7.00008-1>
- Kasmaniar, K., Yana, S., Nelly, N., Fitriliana, F., Susanti, S., Hanum, F., & Rahmatullah, A. (2023). Pengembangan Energi Terbarukan Biomassa dari Sumber Pertanian, Perkebunan dan Hasil Hutan: Kajian Pengembangan dan Kendalanya. *Jurnal Serambi Engineering*, 8(1). <https://doi.org/10.32672/jse.v8i1.5668>
- Lukmadi, F. K., & Sitabuana, T. H. (2022). COP26: Peran Indonesia dalam Dinamika Climate Action terhadap Poros Penanggulangan Perubahan Iklim di Indonesia. *PROSIDING SERINA*, 2(1), 257–262. <https://doi.org/10.24912/pserina.v2i1.18538>

- Morris, J. D., Daood, S. S., Chilton, S., & Nimmo, W. (2018). Mechanisms and mitigation of agglomeration during fluidized bed combustion of biomass: A review. *Fuel*, 230, 452–473. <https://doi.org/10.1016/j.fuel.2018.04.098>
- Murugan, P. C., & Sekhar, S. J. (2017). Species–Transport CFD model for the gasification of rice husk (*Oryza Sativa*) using downdraft gasifier. *Computers and Electronics in Agriculture*, 139, 33–40. <https://doi.org/10.1016/j.compag.2017.05.004>
- Pah, J. M. (2022). *Peningkatan Kualitas Bahan Bakar Padat dari Biomassa Bambu melalui Torefaksi*. Universitas Lampung.
- Pang, S. (2016). Fuel flexible gas production: Biomass, coal and bio-solid wastes. In *Fuel flexible energy generation* (pp. 241–269). Elsevier. <https://doi.org/10.1016/B978-1-78242-378-2.00009-2>
- Parinduri, L., & Parinduri, T. (2020). Konversi biomassa sebagai sumber energi terbarukan. *JET (Journal of Electrical Technology)*, 5(2), 88–92.
- Reddy, K. V., Satya Sree, N. R., Ranjit, P., & Maddela, N. R. (2023). Chapter 23 - Biomass waste and feedstock as a source of renewable energy (M. P. B. T.-G. A. to A. F. for a S. F. Shah (ed.); pp. 325–334). Elsevier. <https://doi.org/https://doi.org/10.1016/B978-0-12-824318-3.00033-3>
- Simorangkir, D. P., & Syaiful, B. (n.d.). *Pirolisis Tandan Kosong Sawit menjadi Bio-Oil dengan Katalis HZSM-5 melalui Proses Hidrodeoksigenasi*.
- Thomson, R., Kwong, P., Ahmad, E., & Nigam, K. D. P. (2020). Clean syngas from small commercial biomass gasifiers; a review of gasifier development, recent advances and performance evaluation. *International Journal of Hydrogen Energy*, 45(41), 21087–21111. <https://doi.org/10.1016/j.ijhydene.2020.05.160>
- Vassilev, S. V., Vassileva, C. G., & Vassilev, V. S. (2015). Advantages and disadvantages of composition and properties of biomass in comparison with coal: An overview. *Fuel*, 158, 330–350. <https://doi.org/10.1016/j.fuel.2015.05.050>
- Warnecke, R. (2020). Gasification of biomass: comparison of fixed bed and fluidized bed gasifier. *Biomass and Bioenergy*, 18(6), 489–497.
- Wheeldon, J. M., & Thimsen, D. (2013). Economic evaluation of circulating fluidized bed combustion (CFBC) power generation plants. In *Fluidized Bed Technologies for Near-Zero Emission Combustion and Gasification* (pp. 620–638). Elsevier. <https://doi.org/10.1533/9780857098801.2.620>



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