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Design and Experimental Study of a Biomass Pellet Gasifier Stove with Heat Recovery System for High Efficiency and Low Emission

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ABSTRACT

Purpose of the study: This study aims to design and test a gasifier-type biomass stove equipped with a heat exchanger system as an innovative effort to increase thermal efficiency and reduce CO emissions.

Methodology: The stove is designed with a special configuration by adding a heat exchanger to the gasifier system. It has dimensions of 700 mm in height, 400 mm in diameter, a combustion chamber height of 300 mm, combustion chamber diameter of 300 mm, an air inlet pipe diameter of 1.5 inches, an exhaust pipe diameter of 3 inches, and a heat exchanger length of 90 cm. Testing was conducted under cold start and hot start conditions, with variations in grate height (250 mm and 300 mm) and air-fuel ratios (0.9, 1.0, and 1.3).

Main Findings: The test results showed that the stove with a heat exchanger system was able to increase the average thermal efficiency to 35.76%, higher than the conventional biomass stove of 28.89%. The CO emissions produced ranged from 19 ppm to 51 ppm, depending on the variation of operation. The optimal conditions were obtained at a grate height configuration of 250 mm and an air-fuel ratio of 1.0 which produced the highest efficiency of 38.02% with CO emissions of 42.78 ppm.

Novelty/Originality of this study: The integration of a heat exchange system into a gasifier-type biomass stove has been shown to enhance thermal efficiency, significantly reduce CO emissions, and yield an optimal combination of parameters that are rarely addressed in previous studies.

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1. INTRODUCTION

Biomass is one of the renewable energy sources that has great potential due to its abundant availability, its renewable nature, and its ability to reduce dependence on fossil fuels [1]-[3]. The increase in global energy needs accompanied by issues of climate change and greenhouse gas emissions encourages the use of biomass as an alternative environmentally friendly energy source [4]-[6]. One form of biomass utilization that is widely used is biomass-fueled stoves for household needs and small industrial scales.

Gasifier-type biomass stoves are one of the choices that are widely developed because they are able to produce pyrolysis gas (producer gas) which is then re-burned to produce heat [7]-[9]. This process has the potential to improve combustion quality compared to direct combustion stoves. However, gasifier-type stoves still face several major problems, namely relatively low thermal efficiency and high pollutant emissions, especially carbon monoxide (CO) which is harmful to health [10]-[12].

The thermal performance and emission characteristics of biomass stoves are greatly influenced by various factors, such as stove design, combustion chamber geometry, air supply, and operational conditions [13]-[15]. Conventional gasifier stoves generally experience suboptimal heat utilization and imperfect combustion, resulting in a lot of heat being wasted with exhaust gas and high CO gas emissions [16]-[18]. Therefore, increasing efficiency and reducing emissions are the main focus in the development of biomass stove technology.

The study by Kole et al. [19] focused on the design and performance evaluation of a rice husk-based biomass stove in a highland area, with an emphasis on adapting the design to extreme environmental conditions. Meanwhile, Mekonnen [20] focused on improving thermal efficiency and reducing emissions through the adoption of an improved biomass stove for sauce cooking purposes in rural Ethiopia. Both studies make important contributions to the development of sustainable biomass stoves, but have not specifically integrated heat recovery systems as an approach to simultaneously improve energy efficiency and reduce emissions. The current study fills this gap by designing and experimentally testing a biomass pellet gasification stove equipped with a heat recovery system, thus optimizing energy utilization while reducing emissions, making it a more comprehensive and efficient solution for clean energy needs in remote areas.

One promising solution is the application of a heat recovery system or heat exchanger system that functions to capture heat from exhaust gas and reuse it to heat the incoming air [21]-[23]. This technology has been widely applied to industrial-scale combustion systems, but is still rarely implemented in small-scale gasifier-type biomass stoves. The integration of a heat exchanger system is expected to improve combustion conditions, increase thermal efficiency, and reduce CO emissions without significantly increasing the complexity of the stove design [24]-26].

In addition to the application of the heat recovery system, the setting of operating parameters such as grate height and air-fuel ratio also plays an important role in achieving optimal combustion performance [27], [28]. Proper control of both parameters can ensure adequate oxygen supply, improve flame stability, and encourage a more perfect combustion process so that efficiency increases and CO gas emissions decrease [29], [30]. Based on this background, this study aims to design and test the performance of a gasifier-type biomass stove equipped with a heat recovery system.

This research has a novelty in the integration of a heat recovery system in a biomass pellet gasification furnace, which has not been widely developed in previous studies. This innovation allows for a significant increase in thermal efficiency while maintaining low emission levels. The urgency of this research lies in the urgent need for energy-efficient and environmentally friendly cooking technology, especially in remote areas that still rely on biomass as the main energy source. By combining high efficiency and reduced emissions in one stove design, this research offers a practical and sustainable solution to improve energy security and air quality in rural communities.

The focus of this study is to evaluate the effect of variations in grate height and air-fuel ratio on the thermal efficiency and CO emission characteristics of the designed stove, with the aim of producing an efficient and environmentally friendly stove for household and small-scale applications.

2. RESEARCH METHOD

2.1. Research Design

The research will be divided into several stages, where the pre-research stage is to conduct a literature study on matters related to biomass stoves. Then, the main research concerns three things, namely design, fabrication, and testing (bolded in the scheme below). Provision of tools and materials and fuel preparation can be done at the same time before fabrication [31]. The things tested include CO exhaust emissions from the stove and the thermal efficiency of the stove. After that, an analysis and evaluation of the research results were carried out, and finally a conclusion was made. The flow diagram in this study can be seen in Figure 1.

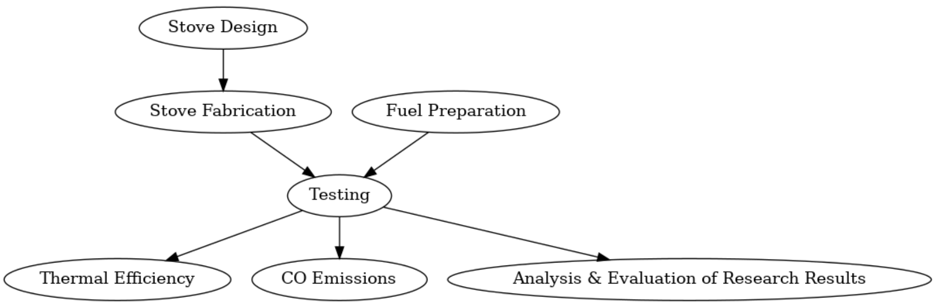

Figure 1. Research Flow Diagram

2.2. Stove Design Stage

The stove design is focused on producing a biomass pellet stove with high efficiency and low emissions. The design includes determining the dimensions of the combustion chamber, air intake system, chimney dimensions, and heat recovery system based on the counter current gas-to-gas heat exchanger principle. The main dimensions of the design results are: overall height 700 mm, overall diameter 400 mm, combustion chamber height 300 mm, and combustion chamber diameter 300 mm. The air inlet pipe has a diameter of 1.5 inches, the chimney pipe has a diameter of 3 inches, and the heat exchanger length is 90 cm. The design considers the need for a balance between air flow velocity, exhaust gas temperature, and flame stability to support optimal thermal efficiency.

2.3. Stove Fabrication

The stove is fabricated using carbon steel and stainless steel pipes that are heat and corrosion resistant [32]. The fabrication process includes cutting, welding, assembling the combustion chamber, installing the primary air flow system, secondary air, and heat exchanger system [33]. A 5 mm diameter wire mesh grill is installed in the combustion chamber to support the combustion process. The chimney is equipped with a knock-down system to facilitate the maintenance process. The entire outer surface of the stove is coated with heat-resistant paint to increase corrosion resistance [34], [35].

2.4. Fuel Preparation

The fuel used is biomass pellets made from dried sawdust. The pellet making process was carried out in previous studies, so in this study the pellets were used in ready-to-use form. Pellets have a water content of <10% and a diameter of ±6 mm, with an average length of 20–30 mm. Pellets were used as fuel in all tests.

2.5. Stove Performance Testing

Testing was conducted in two categories, namely: Thermal efficiency testing was conducted using the Water Boiling Test (WBT) method. 1.5 kg of water was heated in a pan until boiling. The parameters measured included water temperature, fuel mass, evaporated water mass, and ambient temperature [36]. Temperature data was recorded using a K-type thermocouple connected to the ADAM 4018 module for data acquisition [37]-[39]. Efficiency was calculated based on the comparison of the energy absorbed by water with the energy generated from the combustion of biomass pellets [40]-[42]. The carbon monoxide (CO) content in the exhaust gas was measured every 2 minutes using a CO Gas Analyzer (CO Detector 7701). Measurements were carried out simultaneously with the thermal efficiency test. Temperatures at key points, namely flame temperature (T1), heat exchanger inlet gas temperature (T2), chimney outlet gas temperature (T3), and inlet air temperature (T4) were measured for analysis of combustion and heat transfer characteristics.

2.6. Data analysis

The data obtained were analyzed to determine the thermal efficiency of the stove and the amount of CO emissions under various test conditions, including variations in cold start and hot start modes, variations in grate height, and variations in air-fuel ratio. All test results were compared to determine the optimum configuration that produces maximum efficiency and minimum emissions.

3. RESULTS AND DISCUSSION

3.1. Stove Dimensions

The combustion chamber shape is set to be a hollow cylinder like a rocket stove. The area and height of the combustion chamber can be calculated using the formula:

$$H_{CC} = \frac{\sum \Delta \boldsymbol{m_f}}{\boldsymbol{\rho f \; x \; A_{CC}}} \; ... \; (1)$$

The power generated for this stove is adjusted to the daily needs of the community who cook for an average of 1 hour with a power of 2.4 kW, so the mass of fuel used is:

$$P_{av} = \frac{\sum \Delta M_f \; x \; H_c}{t_T} \; \dots \; (2)$$

$$\Delta m_f = \frac{t_T}{H_C} x \; P_{av} \; ... \; (3)$$

With an average biomass heating value of 19.2MJ/kg, the fuel mass is 0.45 kg = 450 grams. According to equation (1) with an average packing density of 1.1 kg/l and an assumed variation in the height of the combustion chamber (Hcc) of 15 - 30 cm, the radius of the combustion chamber is around 0.15 m = 15 cm or the diameter of the combustion chamber is 30 cm.

Then to determine the diameter of the cooking hole (pot hole), it is adjusted to the availability of pots or pans on the market. After the survey, the variations of the available pots include diameters: 18 cm, 20 cm, 22 cm, 24 cm, 26 cm, 28 cm, 30 cm, 31 cm, 34 cm. The use of each diameter is different, for diameters <24cm are generally used for fast use such as boiling instant noodles or brewing coffee/tea.

The calculation of the thickness of the stove uses the heat transfer equation for a cylindrical shape assuming the outside temperature of the stove is 70 °C, so with the dimensions of the cylinder the thickness is 5 cm.

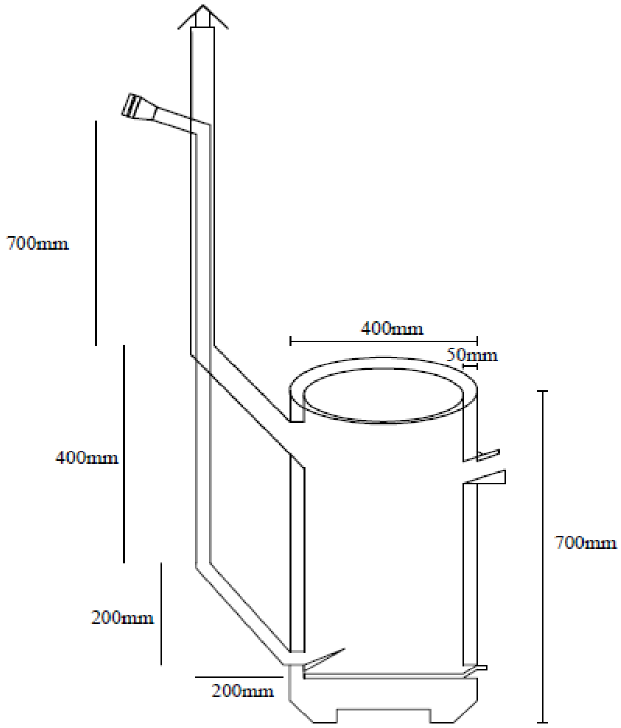

Figure 5. Detailed design of a biomass stove

Overall, the height of the stove when added with the space under the grate with a height of 25 cm and support legs of about 10 cm, then the total height is 70 cm. With a stove thickness of 5 cm, the total diameter of the stove is 40 cm as shown in Figure 5.

For the pipe used as the exhaust chimney and the air inlet pipe that will take the heat from the exhaust chimney, the calculation uses a simple simulation (in Appendix A) of a countercurrent heat exchanger, then the dimensions of the pipe used will be obtained, including:

- Inlet air pipe dimension (inner pipe): Ø 1.5 inch
- Exhaust pipe dimension (outer pipe): Ø 3 inch
- Heat exchange length: 90 cm

3.2. Overall Stove Performance Results

The overall performance of the stove is the result of the average emission efficiency test produced. Which is shown in the following table:

Table 1. Cold Start and Hot Start Test Results

Condition	η (%)	Average CO Emissions
Cold Start	33.75	38.39
Hot Start	35.39	51.63

Table 1 shows the results of the gasifier furnace performance test under cold start and hot start conditions. The thermal efficiency (η) under cold start conditions reached 33.75%, while under hot start it increased to 35.39%. However, the average CO emissions were actually higher under hot start conditions of 51.63 ppm compared to cold start which was only 38.39 ppm. This shows that although the efficiency increased slightly during hot start, the formation of CO emissions also increased significantly.

Table 2. Ui Results of Grate Height Variation

Grate (mm)	η (%)	Average CO Emissions
250	35.85	19.12
300	35.39	51.63

Table 2 shows the effect of grate height variation on efficiency and CO emissions. At a grate height of 250 mm, the thermal efficiency reaches 35.85% with an average CO emission of 19.12 ppm. While at a grate height of 300 mm, the efficiency decreases slightly to 35.39% and CO emissions increase sharply to 51.63 ppm. This shows that a lower grate height (250 mm) produces more complete combustion with lower CO emissions.

Table 3. Results of Air/Fuel Ratio Variation Test (Air Speed)

A/F Ratio	η (%)	Average CO Emissions
0.9	37.84	40.61
1	38.02	42.78
1.3	35.39	51.63

Table 3 presents the effect of variations in the Air/Fuel (A/F) ratio or air velocity on efficiency and CO emissions. At A/F ratios of 0.9 and 1.0, efficiency tends to be higher (37.84% and 38.02%) with CO emissions of 40.61 ppm and 42.78 ppm, respectively. However, when the A/F ratio is increased to 1.3, efficiency decreases to 35.39% and CO emissions increase to 51.63 ppm. This shows that too high an air-fuel ratio can reduce combustion efficiency and increase CO emissions.

3.3. Efficiency Test Results

Efficiency testing is done using the Water Boiling Test (WBT) method. In general, this method produces a ratio of heat produced by fuel to heat received by water to raise its temperature and evaporate it.

Table 4. Cold Start and Hot Start Test Results

Type	Mwater (kg)	Wbiomassa (kg)	Mevap (kg)	Tb (°C)	H (%)
Cold	1.5	0.189	0.240	106	33.75
Hot	1.5	0.190	0.270	104	35.39

Table 5. Grate Height Variation Test Results

Grate (mm)	Mwater (kg)	Wbiomassa (kg)	Mevap (kg)	Tb (°C)	η (%)
250	1.5	0.194	0.28	107	35.85
300	1.5	0.19	0.27	104.5	35.39

Table 6. Results of Water/Fuel Ratio Variation Test

A/F Ratio	Mwater (kg)	Wbiomassa (kg)	Mevap (kg)	Tb (°C)	η (%)
0.9	1.5	0.195	0.31	107.5	37.84
1	1.5	0.189	0.3	106	38.02
1.3	1.5	0.19	0.27	104.5	35.39

The test results in Table 4, Table 5 and Table 6 show that the highest efficiency occurs when the water per fuel ratio is in stoichiometric conditions, but there is still a possibility of an increase between the ratios of 1 and 1.3, because the large amount of excess air can increase the flame temperature according to the basic theory of combustion so that the heat produced is greater can be delivered to the cooking object. In addition, operating conditions that can produce high efficiency when cooking conditions start at high temperatures (hot start). For the height of the fuel from the grate to the stove hole, the efficiency is greater when the height is 250 mm, because the resulting fire can be evenly distributed throughout the surface of the pan compared to if the position is further away. The average efficiency produced is quite high, up to above 35%, this is due to the recovery produced by heat exchange in the exhaust gas chimney.

The results showed that the application of a heat recovery system by adding a heat exchanger to a pellet-based biomass gasification furnace significantly increased thermal efficiency. The average efficiency obtained reached 35.76%, higher than a conventional furnace of 28.89%. This shows that most of the heat energy that was previously wasted through exhaust gas can now be reused to heat the incoming air, thereby increasing combustion and overall energy efficiency. This innovation is a practical solution to improve thermal performance without significantly increasing system complexity.

Variations in the height of the combustion grate have a significant effect on efficiency and CO emissions. In the 250 mm grate height configuration, the highest thermal efficiency of 35.85% was achieved with the lowest CO emissions of 19.12 ppm. Conversely, at a height of 300 mm, there was a significant increase in CO emissions to 51.63 ppm and efficiency decreased. This indicates that the optimal distance between the fuel and the bottom surface of the cooking vessel is very important to maintain perfect combustion and even heat distribution. Testing on three variations of air-fuel ratio (0.9; 1.0; 1.3) showed that the stoichiometric ratio (1.0) produced the best combination of efficiency (38.02%) and CO emissions (42.78 ppm). Too low an air ratio results in incomplete combustion, while excess air (A/F = 1.3) actually reduces efficiency and increases emissions due to flame cooling and disturbances in heat distribution. These results reinforce the importance of controlling the A/F ratio in gasification furnace design so that optimal performance can be achieved.

With the achievement of relatively low CO emissions (19–51 ppm), this stove is considered environmentally friendly and in accordance with the safe CO limit standards for household kitchens. The success of reducing emissions without sacrificing efficiency is a strategic step in the development of sustainable cooking technology [43], [44]. Moreover, the use of biomass pellets as fuel supports reducing dependence on fossil fuels and utilizing agricultural waste productively.

Previous research by Kole et al. [19] focused on the design, development, and performance evaluation of a rice husk-fired biomass stove for highland conditions, highlighting the thermal efficiency and adaptability of the stove in this specific environment. Meanwhile, research by Konieczna et al. [45] evaluated the thermal energy and flue gas emissions of a gasification stove using pine and hemp pellets, focusing mainly on the comparison of alternative fuels and their environmental impacts. Both studies provide important insights into the energy efficiency and emission reduction of biomass stoves, but have limitations in integrating a heat recovery system as a step to significantly improve thermal efficiency. The current research fills the gap by designing and testing a pellet-fired biomass gasification stove equipped with a heat recovery system, aiming to achieve high efficiency while reducing emissions, thus providing a more comprehensive solution in the development of environmentally friendly and energy-efficient biomass stove technology.

This study enriches the literature related to the development of biomass gasification furnaces by presenting the integration of a heat recovery system on a small scale. Although this technology is common in the industrial sector, its application in household stoves is still very limited. Therefore, this research not only offers a new, applicable approach, but also opens up space for the development of future stove designs that are more energy efficient and environmentally friendly.

This research has a positive impact on the development of more efficient and environmentally friendly biomass stove technology, especially for rural communities that still rely on biomass as their main energy source. The integration of the heat recovery system has been proven to increase thermal efficiency by more than 35% and reduce CO emissions to safer levels, thus potentially improving indoor air quality and reducing health risks due to incomplete combustion. However, this research still has several limitations, including limited performance tests on a laboratory scale and controlled environmental conditions, and the lack of long-term tests on material durability and stove performance in daily use. In addition, the test only focused on certain types of biomass pellet fuel, so further studies are needed to test the performance of the stove on various types of biomass and variations in cooking loads.

4. CONCLUSION

The designed biomass stove has a total dimension of 700 mm height, 400 mm diameter, 300 mm combustion chamber height, 300 mm combustion chamber diameter, 1.5 inch air inlet pipe diameter, 3 inch exhaust pipe diameter, and 90 cm heat exchanger length. This stove shows an average increase in thermal efficiency of 35.76%, higher than similar stoves which only reach 28.89%. The CO emissions produced range from 19–51 ppm, where under optimal conditions it still meets the recommended CO emission limit (25 ppm). The best results were achieved at a grate height configuration of 250 mm and an air-fuel ratio of 1.0 (stoichiometric), which provides a balance between maximum efficiency and minimum emissions. Further research is recommended to conduct long-term field tests to evaluate the durability of the material and the performance of the stove under daily use conditions. In addition, exploration of various types of local biomass fuels is needed to test the flexibility and efficiency of the stove more widely.

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REFERENCES

[1] M. Saleem, “Possibility of utilizing agriculture biomass as a renewable and sustainable future energy source,” *Heliyon*, vol. 8, no. 2, p. e08905, 2022, doi: 10.1016/j.heliyon.2022.e08905.

[2] T. Kalak, “Potential Use of Industrial Biomass Waste as a Sustainable,” *Energies*, vol. 16, pp. 1–25, 2023.

[3] J. L. Holechek, H. M. E. Geli, M. N. Sawalhah, and R. Valdez, “A global assessment: can renewable energy replace fossil fuels by 2050?,” *Sustain.*, vol. 14, no. 8, pp. 1–22, 2022, doi: 10.3390/su14084792.

[4] M. A. Destek, S. A. Sarkodie, and E. F. Asamoah, “Does biomass energy drive environmental sustainability? An SDG perspective for top five biomass consuming countries,” *Biomass and Bioenergy*, vol. 149, no. July 2020, p. 106076, 2021, doi: 10.1016/j.biombioe.2021.106076.

[5] U. Shahzad, M. Elheddad, J. Swart, S. Ghosh, and B. Dogan, “The role of biomass energy consumption and economic complexity on environmental sustainability in G7 economies,” *Bus. Strateg. Environ.*, vol. 32, no. 1, pp. 781–801, 2023, doi: 10.1002/bse.3175.

[6] B. A. Gyamfi, I. Ozturk, M. A. Bein, and F. V. Bekun, “An investigation into the anthropogenic effect of biomass energy utilization and economic sustainability on environmental degradation in E7 economies,” *Biofuels, Bioprod. Biorefining*, vol. 15, no. 3, pp. 840–851, 2021, doi: 10.1002/bbb.2206.

[7] A. Kushwah, T. R. Reina, and M. Short, “Modelling approaches for biomass gasifiers: A comprehensive overview,” *Sci. Total Environ.*, vol. 834, no. April, p. 155243, 2022, doi: 10.1016/j.scitotenv.2022.155243.

[8] K. W. Kuttin *et al.*, “Experimental and numerical modeling of carbonized biomass gasification: A critical review,” *Green Carbon*, vol. 2, no. 2, pp. 176–196, 2024, doi: 10.1016/j.greenca.2024.04.003.

[9] F. Patuzzi *et al.*, “State-of-the-art of small-scale biomass gasification systems: An extensive and unique monitoring review,” *Energy*, vol. 223, p. 120039, 2021, doi: 10.1016/j.energy.2021.120039.

[10] E. Picano, C. Mangia, and A. D’Andrea, “Climate Change, Carbon Dioxide Emissions, and Medical Imaging Contribution,” *J. Clin. Med.*, vol. 12, no. 1, pp. 1–9, 2023, doi: 10.3390/jcm12010215.

[11] R. Tang *et al.*, “Air quality and health co-benefits of China’s carbon dioxide emissions peaking before 2030,” *Nat. Commun.*, vol. 13, no. 1, pp. 1–9, 2022, doi: 10.1038/s41467-022-28672-3.

[12] S. D. Lowther *et al.*, “Low level carbon dioxide indoors—a pollution indicator or a pollutant? A health-based perspective,” *Environ. - MDPI*, vol. 8, no. 11, pp. 1–25, 2021, doi: 10.3390/environments8110125.

[13] W. Gao *et al.*, “Comprehensive Review on Thermal Performance Enhancement of Domestic Gas Stoves,” *ACS Omega*, vol. 8, no. 30, pp. 26663–26684, 2023, doi: 10.1021/acsomega.3c01628.

[14] M. Holubčík, N. Čajová Kantová, J. Jandačka, and A. Čaja, “The Performance and Emission Parameters Based on the Redistribution of the Amount of Combustion Air of the Wood Stove,” *Processes*, vol. 10, no. 8, 2022, doi: 10.3390/pr10081570.

[15] S. Bentson, D. Evitt, D. Still, D. Lieberman, and N. MacCarty, “Retrofitting stoves with forced jets of primary air improves speed, emissions, and efficiency: Evidence from six types of biomass cookstoves,” *Energy Sustain. Dev.*, vol. 71, pp. 104–117, 2022, doi: 10.1016/j.esd.2022.09.013.

[16] M. I. I. Rabby *et al.*, “Thermal performance of gasifier cooking stoves: A systematic literature review,” *F1000Research*, vol. 12, pp. 1–27, 2023, doi: 10.12688/f1000research.126890.2.

[17] D. T. Ebissa and E. Getahun, “Development and Performance Evaluation of Biomass-Based Injera Baking Gasifier Stove: A Case Study of Clean Cooking Technologies in Ethiopia,” *Sci. World J.*, vol. 2024, 2024, doi: 10.1155/2024/1524398.

[18] A. S. Tomlin, “Air Quality and Climate Impacts of Biomass Use as an Energy Source: A Review,” 2021. doi: 10.1021/acs.energyfuels.1c01523.

[19] A. T. Kole, B. A. Zeru, E. A. Bekele, and A. V. Ramayya, “Design, development, and performance evaluation of husk biomass cook stove at high altitude condition,” *Int. J. Thermofluids*, vol. 16, no. November, p. 100242, 2022, doi: 10.1016/j.ijft.2022.100242.

[20] B. A. Mekonnen, “Thermal efficiency improvement and emission reduction potential by adopting improved biomass cookstoves for sauce-cooking process in rural Ethiopia,” *Case Stud. Therm. Eng.*, vol. 38, no. July, p. 102315, 2022, doi: 10.1016/j.csite.2022.102315.

[21] C. Ononogbo *et al.*, “Opportunities of waste heat recovery from various sources: Review of technologies and implementation,” 2023, *Elsevier Ltd*. doi: 10.1016/j.heliyon.2023.e13590.

[22] O. Farhat, J. Faraj, F. Hachem, C. Castelain, and M. Khaled, “A recent review on waste heat recovery methodologies and applications: Comprehensive review, critical analysis and potential recommendations,” 2022, *Elsevier Ltd*. doi: 10.1016/j.clet.2021.100387.

[23] H. Nagpal, J. Spriet, M. K. Murali, and A. McNabola, “Heat recovery from wastewater—a review of available resource,” *Water (Switzerland)*, vol. 13, no. 9, pp. 1–26, 2021, doi: 10.3390/w13091274.

[24] M. Li *et al.*, “A Comprehensive Review of Thermal Management in Solid Oxide Fuel Cells: Focus on Burners, Heat Exchangers, and Strategies,” *Energies*, vol. 17, no. February, pp. 1–30, 2024.

[25] T. Nega, A. Tesfaye, and P. Paramasivam, “Design and CFD modeling of gasifier stove combined with heat exchanger for water heating application,” *AIP Adv.*, vol. 12, no. 4, pp. 1–9, 2022, doi: 10.1063/5.0081001.

[26] H. Abedi, C. Xisto, I. Jonsson, T. Grönstedt, and A. Rolt, “Preliminary Analysis of Compression System Integrated Heat Management Concepts Using LH2-Based Parametric Gas Turbine Model,” *Aerospace*, vol. 9, no. 4, 2022, doi: 10.3390/aerospace9040216.

[27] Q. Peng *et al.*, “Summary of Turbocharging as a Waste Heat Recovery System for a Variable Altitude Internal Combustion Engine,” *ACS Omega*, vol. 8, no. 31, pp. 27932–27952, 2023, doi: 10.1021/acsomega.3c02818.

[28] K. C. Cho, K. Y. Shin, J. Shim, S. S. Bae, and O. D. Kwon, “Performance Analysis of a Waste Heat Recovery System for a Biogas Engine Using Waste Resources in an Industrial Complex,” *Energies*, vol. 17, no. 3, pp. 1–15, 2024, doi: 10.3390/en17030727.

[29] A. Al-qazzaz *et al.*, "An approach of analyzing gas and biomass combustion: Positioned of flame stability and pollutant reduction," *Results Eng.*, vol. 23, no. June, pp. 1–9, 2024, doi: 10.1016/j.rineng.2024.102823.

[30] H. Wang *et al.*, "Key CO2 capture technology of pure oxygen exhaust gas combustion for syngas-fueled high-temperature fuel cells," *Int. J. Coal Sci. Technol.*, vol. 8, no. 3, pp. 383–393, 2021, doi: 10.1007/s40789-021-00445-1.

[31] A. Tang, L. Crisci, L. Bonville, and J. Jankovic, "An overview of bipolar plates in proton exchange membrane fuel cells," *J. Renew. Sustain. Energy*, vol. 13, no. 2, pp. 1–17, 2021, doi: 10.1063/5.0031447.

[32] J. N. Sultan, M. K. Abbas, M. Abd-Al Kareem Ibrahim, E. T. Karash, A. M. Ali, and H. A. Ibrhim, "Corrosion Behavior of Thermal Seamless Carbon Steel Boiler Pipes," *Ann. Chim. Sci. des Mater.*, vol. 45, no. 5, pp. 399–405, 2021, doi: 10.18280/acsm.450506.

[33] V. E. Udoh, I. Ekanem, and A. E. Ikpe, "A review of welding and fabrication processes and resulting impacts on environmental sustainability : risk and control measures," *Risk Assess. Manag. Decis.*, vol. 1, no. 1, pp. 142–153, 2024, doi: 10.48314/ramd.v1i1.40.

[34] I. Felhősi *et al.*, "Corrosion protection and heat resistance of paints for outdoor use," *Materials (Basel).*, vol. 16, no. 7, pp. 1–16, 2023, doi: 10.3390/ma16072753.

[35] H. A. El-Wahab *et al.*, "Efficacy of zinc and copper oxide nanoparticles as heat and corrosion-resistant pigments in paint formulations," *Sci. Rep.*, vol. 14, no. 1, pp. 1–14, 2024, doi: 10.1038/s41598-024-74345-0.

[36] Z. Lei and T. Langrish, "Energy and exergy analysis for a laboratory-scale closed-loop spray drying system: Experiments and simulations," *Dry. Technol.*, vol. 43, no. 1–2, pp. 228–247, 2024, doi: 10.1080/07373937.2024.2387840.

[37] M. Panahi, H. R. Heydari, and G. Karimi, "Effects of micro heat pipe arrays on thermal management performance enhancement of cylindrical lithium-ion battery cells," *Int. J. Energy Res.*, vol. 45, no. 7, pp. 11245–11257, 2021, doi: 10.1002/er.6604.

[38] B. Bakri, H. Benguesmia, H. Nasraoui, and Z. Driss, "Experimental study of solar chimney power plant," *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 101, no. 1, pp. 207–214, 2023, doi: 10.37934/arfmts.101.1.207214.

[39] S. Sheykhbaglou, A. Ghahremani, S. Tabejamaat, and M. Sánchez-Sanz, "Comparative study of combustion and thermal performance of a meso-scale combustor under co- and counter-rotating fuel and oxidizer swirling flows for micro power generators," *Heliyon*, vol. 10, no. 2, pp. 1–18, 2024, doi: 10.1016/j.heliyon.2024.e24250.

[40] G. Jia, "Combustion characteristics and kinetic analysis of biomass pellet fuel using thermogravimetric analysis," *Processes*, vol. 9, no. 5, pp. 1–12, 2021, doi: 10.3390/pr9050868.

[41] C. Scott, T. M. Desamsetty, and N. Rahmanian, "Unlocking power: impact of physical and mechanical properties of biomass wood pellets on energy release and carbon emissions in power sector," *Waste and Biomass Valorization*, vol. 16, no. 1, pp. 441–458, 2024, doi: 10.1007/s12649-024-02669-z.

[42] J. Trnka, M. Holubčík, N. Č. Kantová, and J. Jandačka, "Energy performance of a rotary burner using pellets prepared from various alternative biomass residues," *BioResources*, vol. 16, no. 4, pp. 6737–6749, 2021, doi: 10.15376/biores.16.4.6737-6749.

[43] T. P. Böttcher, S. Empelmann, J. Weking, A. Hein, and H. Krcmar, "Digital sustainable business models: Using digital technology to integrate ecological sustainability into the core of business models," *Inf. Syst. J.*, vol. 34, no. 3, pp. 736–761, 2024, doi: 10.1111/isj.12436.

[44] P. K. Sarker, "Microorganisms in Fish Feeds, Technological Innovations, and Key Strategies for Sustainable Aquaculture," *Microorganisms*, vol. 11, no. 2, pp. 1–19, 2023, doi: 10.3390/microorganisms11020439.

[45] A. Konieczna, K. Mazur, A. Koniuszy, A. Gawlik, and I. Sikorski, "Thermal energy and exhaust emissions of a gasifier stove feeding pine and hemp pellets," *Energies*, vol. 15, no. December, pp. 1–17, 2022, doi: https://doi.org/10.3390/en15249458.