



Experimental Analysis of a Solar-Powered Biomass Stove with Flame Sensor Feedback Control Using Wood Chips as Fuel

Daniel Uguru-Okorie¹, Kehinde Adisa², Abiodun Adebimpe¹

¹Department of Mechatronics Engineering, Federal University Oye-Ekiti, Ekiti State, Nigeria

²Department of Mechatronics Engineering, Lagos State University of Science and Technology, Ikorodu, Nigeria

Corresponding author: daniel.uguru-okorie@fuoye.edu.ng

Article history: Received: 27-12-25, Revised: 13-04-26, Accepted: 12-05-26, Published: 20-05-26

Abstract

A common method of wood chip usage is through combustion for the production of heat, and this can be channelled to various uses such as electricity production, space heating, water heating and cooking. The production of greenhouse gases and particulate matter are two examples of how incomplete combustion of wood chips can harm the environment. Therefore, this work explores technologies that enhance the combustion of biomass, which leads to the reduction of the negative environmental impact of incomplete combustion. The biomass stove with a solar-powered blower, regulated by a microcontroller (Arduino Uno) which receives signals from an IR flame sensor, was developed. The experiment carried out was a water-boiling experiment, using wood chips as fuel. For measurements, the stainless steel probe digital thermometer, electronic kitchen scale and stopwatch were used for temperature, mass and boiling time, respectively. Wood chip residues from both cooking units were weighed after each water-boiling test. The performance of the stoves was evaluated based on improvement in boiling time (τ_b), burning rate (Br), thermal efficiency (η_{th}) and the specific fuel consumption (SFC). Improvement in boiling time of 39.4%, 30.4%, 11.6%, 1.1% and 9.7%, respectively, was obtained over the stove without a blower for the same masses of boiled water ranging from 1 kg to 5 kg. The burn rate of the flame sensor-controlled blower ranged from 4.7×10^{-4} kg/s to 6.5×10^{-4} kg/s, showing improvement over the stove without a blower. The thermal efficiency of the flame sensor-controlled blower ranged from 2.8 to 10.3%, while that without a blower ranged from 2.8 to 6.7%. The specific fuel consumption (SFC) ranged from 0.106 to 0.149 kg/s for the flame sensor-controlled blower, while that without a blower ranged from 0.111 to 0.229 kg/s. The results obtained showed that the biomass stove with a flame-sensor-controlled blower gave improved performance over that without a blower in all the evaluations.

Keywords: Biomass; cooking; microcontroller; solar; wood chip

1. Introduction

Biological materials, such as wood, agricultural waste, or municipal garbage, are the sources of biomass, a renewable energy source (Uguru-Okorie et al., 2024; Yi et al., 2021). A common method of biomass usage is through combustion for the production of heat that can be channelled to various uses such as electricity production, space heating, and water heating (Kumar et al., 2021). Wood chips are obtained from the milling of lumber and furniture production (Babalola et al., 2018; Darmawan et al., 2018). Though they are biodegradable, the dump sites could be significant sources of methane formation and liberation, a greenhouse gas. The production of greenhouse gases and particulate matter are two examples of how incomplete combustion of wood chips can harm the environment (He et al., 2021; Yao et al., 2023).

While the concept of smart burners is established, recent research, including the application of fuzzy logic controllers (Bahar et al., 2020) and artificial intelligence (Wang et al., 2021), has significantly advanced their performance by enabling real-time adjustments to air-to-fuel ratios and input rates. Despite these benefits, challenges remain regarding the high cost of implementing advanced sensors and the need for better adaptability across diverse biomass fuel types (Kumar et al., 2021; Yi et al., 2021). Nevertheless, continued development of smart biomass burners is a critical pathway towards achieving a sustainable, clean energy infrastructure that balances environmental responsibility with operational reliability.

It is, therefore, important to develop technologies that enhance the combustion of biomass, which leads to the reduction of the negative environmental impact of incomplete combustion, using majorly locally sourced materials. The solution being the development of a smart biomass burner.

2. Materials and Methods

2.1 Mechanical Design

The stove was constructed using locally sourced materials, among which are mild steel, galvanized steel, and aluminum. Having specified the materials needed for the construction of the smart biomass burner, the portable structure was built up to a carrying capacity of 35 kg. The frame structure, made of mild steel, with the pot seat has the following dimensions: 154 mm by 154 mm for the inside, 214 mm by 214 mm for the outside, and 79 mm length by 12 mm height of the pot suspender.

Table 1 shows the smart biomass burner parts list, including the materials used for various parts. The table also includes the quantity of the part available in the complete construction work.

2.1.1 Description of Biomass Burner Parts

The various fabricated components of the biomass burner are described in this section.

Table 1 Smart Biomass Burner Parts List

Item	Quantity	Part Number	Description
1	1	Ash Mesh	Mild Steel
2	1	Ash Rack	Galvanize Steel
3	1	Cone	Mild Steel
4	1	Frame Structure	Mild Steel
5	1	Biomass (Wood Chip) Guide	Ceramics
6	1	Body Cover	Aluminum
7	1	Air Exchanging Unit	Standard
8	8	AS 1110-M6 X 12	ISO metric hexagon precision bolts and screws
9	8	ANSI B18.2.4.2M – M6 X 1	Metric Hex Nuts Styles 2
10	2	Air Guide	Mild Steel
11	2	Casing	Plastic
12	2	Insulator	Wood
13	2	Fan	Standard
14	1	Pot Seat	Mild Steel

(i) Ash Mesh

The ash rack is the ash mesh that allows ash to fall into the rack from the biomass (wood chip) guide after combustion. The ash mesh is square with sides of 210 mm and a thickness of 2 mm. Holes of 6 mm diameter are evenly arrayed from the center of the mesh outwards.

(ii) Ash rack

The ash rack measures 210 mm by 210 mm by 100 mm and is made of galvanized steel. The ash rack can be removed from the stove to dispose of ash whenever it is filled.

(iii) Cone

The cone is placed above the biomass (wood chip) guide. The cone has diameters of 110 mm at the top and 210 mm at the bottom with a height of 150 mm. The function of the cone is to direct heat to the pot seat where the cooking pot is placed. The cone's height extends upwards and nearly touches the pot seat to ensure minimal heat is lost to the surroundings. This enhances the stove's overall efficiency. The cone has been perforated at the top instead of being left hollow to slow the air rising from the biomass guide, where combustion occurs. Slowing the air is necessary because it carries some of the heat energy from the

combustion of biomass/wood chips, and slowing it ensures that most of this heat is used for cooking.

(iv) Biomass/wood chip guide

The biomass (wood chip) guide is cylindrical in shape with an external diameter of 210 mm, an internal diameter of 200 mm, and a height of 160 mm. The biomass (wood chip) guide is made of ceramics, which serves the crucial function of retaining heat within the stove and making it available for cooking. Retaining heat ensures minimal heat is lost to the surroundings through conduction and radiation (Oketch *et al.*, 2022). The heat-retaining property of the ceramics used to make the biomass (wood chip) guide is crucial in enhancing the efficiency of the stove.

(v) Body Cover

The housing comprises a mild steel frame and an aluminum cover. The cover is made of aluminum to reduce the overall weight of the stove for easy portability. The frame has a square cross-section of sides of 214 mm, a height of 450 mm, and a thickness of 30 mm.

(vi) Air-exchanging unit

The air-exchanging unit has an artificial air supply system for the stove. The air is supplied by a fan that is powered by solar energy. The stove's air supply ensures complete combustion of the biomass (wood chip), thereby reducing indoor pollution.

(vii) Air guide

Air guide is an important part of the smart biomass burner. An air guide is used to provide an airtight seal between the fans and the burner in order to enhance the air-to-fuel ratio in the combustion chamber.

(viii) Pot seat

The pot seat is made of mild steel, and it is where the cooking pot is placed. The pot seat has the following dimensions 154 mm by 154 mm in, 214 mm by 214 mm out, 79 mm length by 12 mm height of pot suspender.

2.2 Electrical and Electronics Section Design

The same biomass burner used by Uguru-Okorie, et al., (2024) was used for the experiments. The biomass stove with a solar-powered blower, regulated by a microcontroller (Arduino Uno) that receives signals from an IR flame sensor, was developed. The flame sensor's sensitivity is adjusted to respond to a yellowish flame. When a yellowish flame is detected, the blower is activated to blow for one minute; thereafter, the sensor checks to detect the flame color. The mechanical component of the system is as shown in Figure 1, while the block diagram of the system is shown in Figure 2. The electronic components include an IR flame sensor, Arduino Uno, relay module, DC fans, PV module, solar charger controller, and battery.

The Arduino UNO used is a microcontroller board based on the ATmega328P. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button. The relay module is ideal for single-chip microcontroller and household appliance control applications. The module can control DC and AC signals, including a 220V AC load. The specifications of the one-channel 5V relay module are a TTL control signal level of 5V-12V and a relay voltage of 5V. The flame sensor used detects flame at a wavelength within the range of 760 nm – 1100 nm from the light source.

2.2.1 Power Consumption and Energy Storage

The developed system had two DC fans with dimensions of 280x280x80 mm and specifications of 12 V and 0.7 A integrated. A 12V 7Ah sealed lead-acid battery (AGM), the B.B. Battery BP7-12, served as its energy storage unit, while the charging and powering of the electrical and electronics components of the stove was done through the solar unit of the systems during the day and by the battery when available solar energy was insufficient.

2.3 Experimental Procedure

The experiments carried out were water-boiling experiments, using an aluminum cooking pot and wood chips as fuel. The same pot was used throughout the experiments. The Stainless Steel Probe Digital Thermometer with a measuring range of -40°C to 300°C and a resolution of 0.1°C was used to measure the temperature of water at boiling point. The measurement of the mass of water to boil and the corresponding mass of wood chips to use was carried out with the electronic kitchen scale (SF-400 model) with a resolution of 1 g. The boiling time was measured with a stopwatch (Winner W-308 model). Masses of water ranging from 1 kg to 5 kg were used, while wood chips of mass 1 kg were used as fuel in both stoves. Wood chip residues from both cooking units were weighed after each water-boiling test.

1- Ash Mesh, 2- Ash Rack, 3- Cone, 4- Frame Structure, 5- Biomass (Wood Chip) Guide, 6- Body Cover, 7- Air Exchanging Unit, 8- ISO metric hexagon precision bolts and screws, 9- Metric Hex Nuts Styles 2, 10- Air Guide, 11- Casing, 12- Insulator, 13- Fan, 14- Pot Seat

2.4 Performance Evaluation

The performance of the biomass stove with a flame sensor-controlled blower and that without a blower was evaluated based on improvement in boiling time, burning rate (B_r), thermal efficiency (η_{th}), and the specific fuel consumption

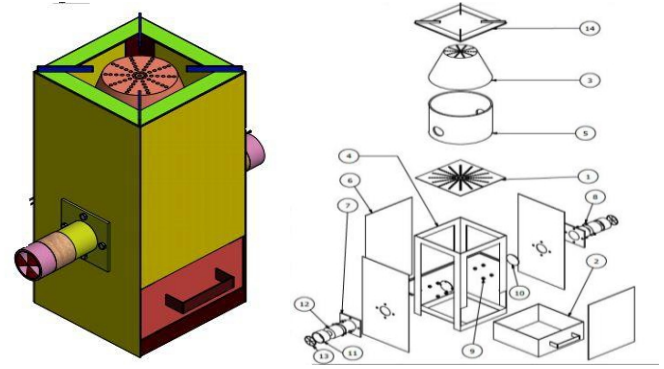


Figure 1: CAD design and exploded view of smart biomass stove

(SFC) as shown in Equations 1-5. The subscript TBB denotes parameters for the burner without a blower, while SBB represents parameters from the flame sensor-controlled blower.

$$\text{Improvement in Boiling Time}(\tau_b) = \frac{\text{Time}_{TBB} - \text{Time}_{SBB}}{\text{Time}_{SBB}} \times 100\% \quad (1)$$

The block diagram of the system set-up is shown in Figure 2.

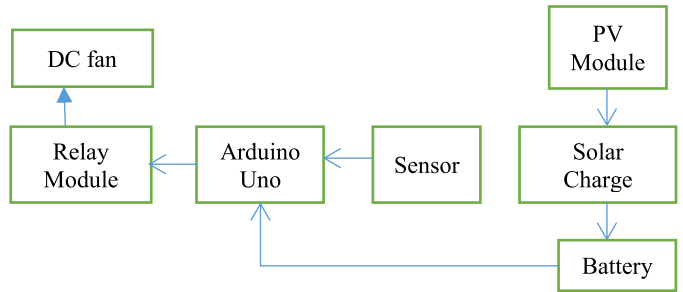


Figure 2: Block diagram of the smart biomass stove

The burn rate, thermal efficiency, and the specific fuel consumption (SFC) using Bolaji and Olalusi's (2009) models. The values of moisture content and net calorific values of 9.52% and 22.5 MJ were used for the wood chip calculations based on the findings of Akhator et al. (2017). The distance between the fuel bed and the pot was kept as small as possible to maximize heat transmission and reduce heat losses.

According to Bolaji and Olalusi (2009), the thermal efficiency of the stove, η_{th} , is calculated using the Equation 2:

$$\eta_{th} = \frac{m_{iw}C(T_f - T_i) + (m_{iw} - m_{fw})L}{B_r \times t \times Q_{net}} \quad (2)$$

where m_w = initial mass of water in the pot, kg; m_{fw} = final mass of water in the pot, kg; T_i = initial temperature of the water, 25 °C; T_f = final temperature of the water, 100 °C; C = specific heat capacity of water (kJ/kgK); L = latent heat of vaporization of water at 100 °C (kJ/kg).

B_r is the burning rate and is calculated using Equation 3:

$$B_r = \frac{100(m_i - m_f)}{(100 + M)t} \quad (3)$$

where m_i = initial mass of fuel at the start of the test, kg; m_f = final weight of fuel at the end of the test, kg; M = moisture content of the fuel, %; t = total time taken for burning fuel, s

Since the experiments were concluded immediately after water attained a temperature of 100 °C, losses due to evaporation were negligible. The model for the determination of thermal efficiency can be given by Equation 4:

$$\eta_{th} = \frac{m_{iw}C(T_f - T_i)}{B_r \times t \times Q_{net}} \quad (4)$$

The controlled cooking test, according to Bolaji and Olalusi (2009), was used to determine the specific fuel consumptions of the burners. The specific fuel consumption (SFC) gives the amount of fuel needed to boil 1 kg of water. The specific fuel consumption (SFC) is expressed in Equation 5:

$$\text{SFC} = \frac{\text{Mass of Fuel consumed (kg)}}{\text{Mass of water boiled (kg)}} \quad (5)$$

3. Results and Discussion

3.1 Boiling Time Test for Flame Sensor-Controlled Blower and Conventional Stove

The developed flame sensor-controlled biomass stove is shown in Figure 3. Water boiling tests were conducted using 1 kg of wood chips as fuel for water masses ranging from 1 kg to 5 kg. The time taken to boil each mass of water using the flame sensor-controlled blower stove (SBB) and the stove without a blower (TBB) is presented in Figure 4.



Figure 3: Developed flame sensor-controlled biomass stove and experimental setup (a) Complete experimental setup with solar panel and controller (b) Biomass stove with cooking pot

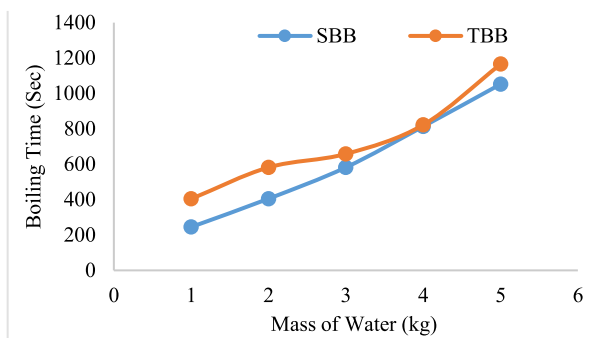


Figure 4: Boiling time results for various masses of water using 1 kg of wood chips

The boiling time increased with increasing mass of water for both stoves. The flame sensor-controlled blower stove showed improvement in boiling time compared to the conventional stove, ranging from 1.10% to 39.36% as presented in Table 2. The highest improvement (39.36%) was recorded with 1 kg of water, while the lowest improvement (1.10%) occurred with 4 kg of water.

Table 2: Percentage improvement in boiling time of the stove with flame sensor-controlled blower compared to the stove without blower

Mass of Water (kg)	Improvement in Boiling Time (τ_b) (%)
1	39.36
2	30.41
3	11.55
4	1.10
5	9.70

3.2 Burn Rate Determination

The burn rate was determined using data of the mass of fuel before and after boiling of water of the biomass stove with a flame sensor-controlled blower and one without a blower, as shown in Figure 5. The burn rate of a flame sensor-controlled blower ranged from to, while that without a blower ranged from to. The burn rate peaked when 2 kg of water was boiled and thereafter reduced with an increase in the mass of water boiled for the biomass stove with a flame sensor-controlled blower. When compared to the stove without a blower, an increase in burn rate was observed in the boiling test for 1 and 2 kg masses of water, which could be attributed to faster picking up of combustion as a result of the assistance of the blower. A reduction in the burn rate, compared to the traditional stove, was observed in the boiling test for 3 and 4 kg masses of water, while in the 5 kg water-

boiling test, the burn rate was relatively the same. The result shows that the flame sensor-controlled blower stoves perform optimally in conditions where a sufficient quantity of wood chips is in the combustion chamber.

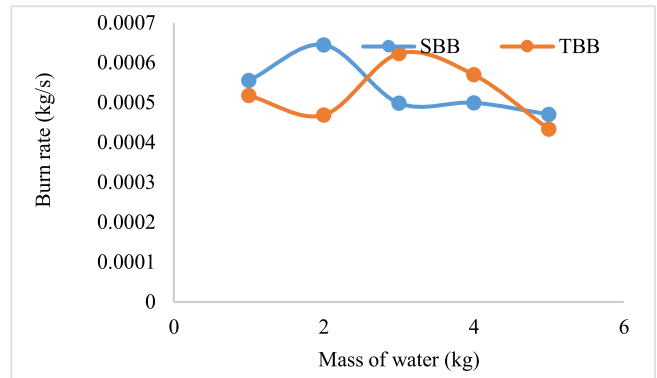


Figure 5: Burn rate for various mass of water using 1kg of wood chip.

3.3 Thermal Efficiency Determination

The thermal efficiency, which indicates how well heat is delivered from the fuel to the pot were determined for the biomass stove with a flame sensor-controlled blower and that without a blower as shown in figure 6. The thermal efficiency of the flame sensor-controlled blower ranged from 2.8 to 10.3% while that without a blower ranged from 2.8 to 6.7%. The thermal efficiencies of the stoves were relatively the same at 2kg and 5kg of water boiling tests while the biomass stove with a flame sensor-controlled blower showed improved thermal efficiencies at water boiling tests of masses 1kg, 2kg and 4kg.

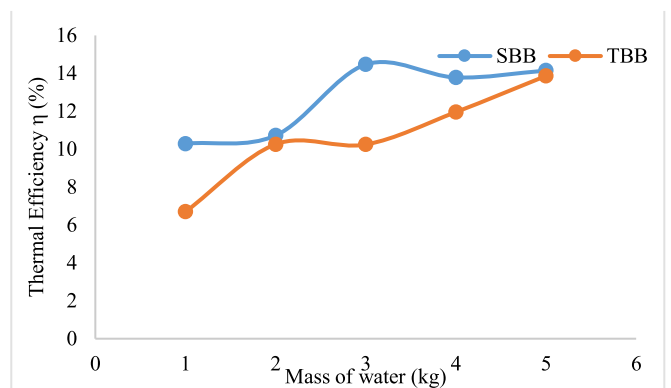


Figure 6: Thermal efficiencies for various mass of water using 1kg of wood chip.

3.4 Specific Fuel Consumption (SFC) Determination

The results obtained for the mass of fuel consumed using 1 kg of wood chips (fuel) for the biomass stove with a flame sensor-controlled blower and those without a blower are shown in figure 7. The specific fuel consumption (SFC) of the stoves reduced with an increase in the mass of water boiled. The result in Figure 7 shows that the biomass stove with a flame sensor-controlled blower had a lower SFC compared to that without a blower, with similarities in values occurring at 2 kg and 5 kg water boiling tests. The specific fuel consumption (SFC) ranged from 0.106 to 0.149 kg/s for the flame sensor-controlled blower, while that without a blower ranged from 0.111 to 0.229 kg/s. The lower SFC could be attributed to improved combustion in the biomass stove with a flame sensor-controlled blower.

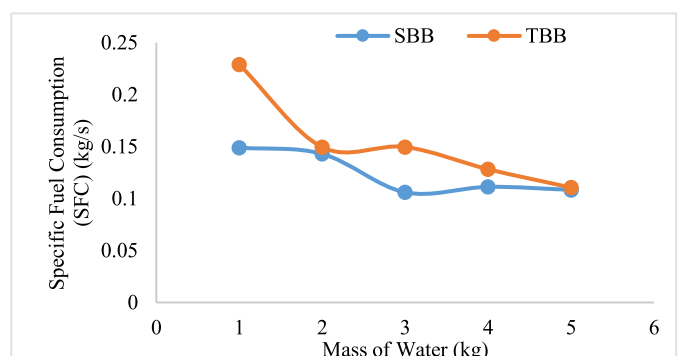


Figure 7: Specific Fuel Consumption (kg/s) with Mass (kg) of Water Boiled

4. Conclusion

A solar-powered biomass stove with flame sensor feedback control using wood chips as fuel has been developed, and boiling water experiments have been carried out using various masses of water ranging from 1 kg to 5 kg. The performance of the stoves was evaluated based on improvement in boiling time (t), burning rate (Br), thermal efficiency (η_{th}) and specific fuel consumption (SFC). Improvements in boiling time of 39.4%, 30.4%, 11.6%, 1.1% and 9.7%, respectively, were obtained over the stove without a blower for the same masses of boiled water. The burn rate of the stove with a flame sensor-controlled blower ranged from to, showing improvement over the stove without a blower. The thermal efficiency of the stove with a flame sensor-controlled blower ranged from 2.8 to 10.3%, while that without a blower ranged from 2.8 to 6.7%, and the specific fuel consumption (SFC) ranged from 0.106 to 0.149 kg/s for the flame sensor-controlled blower stove and that without a blower ranged from 0.111 to 0.229 kg/s. The results obtained showed that the biomass stove with a flame-sensor-controlled blower gave improved performance over that without a blower in all the metrics used for evaluation.

References

- Akhaton, E. P., Obanor, A. I., & Ugege, A. O. (2017). Physico-chemical properties and energy potential of wood wastes from sawmills in Benin metropolis, Nigeria. *Nigerian Journal of Technology*, 36(2), 452-456.
- Babalola, A. A., Adeyemi, H. O., Lawal, N. S., Adetifa, B. O., & Adama, K. O. (2018). Characterization of small scale lumber saw mills in a rural area in Nigeria. *Journal of Experimental Research*, 6(3), 12-21.
- Bahar, R., Hassanzadeh Khayyat, M., & Ghobadian, B. (2020). Performance evaluation of a smart biomass burner with fuzzy logic control for small-scale combustion applications. *Energy Conversion and Management*, 209, 112700. <https://doi.org/10.1016/j.enconman.2020.112700>
- Bolaji, B. O., & Olalusi, A. P. (2009). Development of an improved coal stove for cooking in developing countries, *AUJ.T* 12(3):182-187.
- Darmawan, W., Azhari, M., Rahayu, I. S., Nandika, D., Dumasari, L., Malela, I., & Nishio, S. (2018). The chips generated during up-milling and down-milling of pine wood by helical router bits. *Journal of the Indian Academy of Wood Science*, 15, 172-180.
- He, R., Chen, X., Han, L., & Chen, H. (2021). Effect of biomass combustion on atmospheric pollution in China. *Journal of Cleaner Production*, 315, 128180. <https://doi.org/10.1016/j.jclepro.2021.128180>
- Kumar, P., Agrawal, S., & Singh, S. K. (2021). Technological advances in biomass combustion for electricity generation: A review. *Energy Reports*, 7, 1365-1383. <https://doi.org/10.1016/j.egyr.2021.04.006>
- Uguru-Okorie D. C., Adisa K., Adebimpe A. (2024) Performance Evaluation of a Smart Biomass Stove using Charcoal as Fuel with Solar Powered Blower. *Equity Journal of Science and Technology*, 11(1), 71-73.
- Wang, X., Wang, C., Gao, C., & Feng, J. (2021). An AI-based smart burner for biomass combustion optimization. *Energy Conversion and Management*, 242, 114351. <https://doi.org/10.1016/j.enconman.2021.114351>
- Yao, W., Zhao, Y., Chen, R., Wang, M., Song, W., Yu, D. (2023). Emissions of Toxic Substances from Biomass Burning: A Review of Methods and Technical Influencing Factors. *Processes* 11(3), 853.
- Yi, W., Li, Y., Chen, Y., Li, X., & Yang, W. (2021). Biomass energy systems: A review of technology, application, and economic analysis. *Renewable and Sustainable Energy Reviews*, 138, 110547. <https://doi.org/10.1016/j.rser.2020.110547>