Biomass Co-firing in Coal Power Plants: Analyzing Combustion Characteristics and Emission Reductions

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Abstract: Co-firing biomass in coal-fired power plants presents a viable method to reduce reliance on fossil fuels and promote the use of thermal renewable energy sources, aligning with carbon neutrality and net-zero emission goals. This study conducts a comprehensive combustion analysis of various biomass-coal mixtures to evaluate their effectiveness. Mixtures containing 1%, 3%, and 5% biomass from rice husks, ironwood sawdust, and teak sawdust were analyzed. The results indicate that incorporating biomass with coal decreases the theoretical air requirements for combustion, thereby enhancing combustion efficiency and reducing emissions. Specifically, each 1% increase in biomass content results in a reduction in theoretical air requirements by 2.4% for rice husks, 0.3% for ironwood sawdust, and 0.9% for teak sawdust. Moreover, biomass addition lowers the fuel's calorific value and ignition point, leading to faster ignition and more efficient burning in the combustion chamber. These findings underscore the need for further research to optimize biomass-coal co-firing, including long-term operational studies at power stations and life cycle impact assessments to understand the full environmental, social, and economic implications. The insights from this study are instrumental in developing more efficient combustion systems and optimizing biomass-coal mixtures for better performance. This research provides valuable references for advancing biomass co-firing in coal-fired power plants, particularly in Indonesia, contributing to a more sustainable and environmentally friendly power generation strategy.

Keywords: biomass; Coal-fired power plant (CFPP); co-firing; renewable thermal-energy sources; sustainable energy development; thermal analysis

1. Introduction

In certain nations, the usage of coal as the primary energy source is increasing along with rapid economic development. This trend is particularly notable in power plants, the cement industry, and other industrial sectors[1)]. Governments, especially those focusing on diversification and conservation, are exploring environmentally friendly alternatives to traditional coal usage. One such method is co-firing technology, which involves the co-combustion of coal with environmentally sound biomass[2)].

The Indonesian government has committed to implementing clean energy by increasing usage and promoting investment in renewable sources[3)]. Co-firing biomass in coal-fired power plants (CFPP) is a strategic effort to reduce greenhouse gas emissions and enhance the utilization of renewable energy[4]. This technology plays a crucial role within the framework of sustainable development in the energy sector[5]. The potential of biomass co-firing extends beyond environmental benefits. Additionally, the use of biomass in co-firing contributes to carbon neutrality. Biomass, being a renewable resource, absorbs carbon dioxide during its growth phase, offsetting the emissions produced during combustion. This carbon cycle makes biomass as a carbon-neutral fuel, which is essential for achieving net-zero emissions goals. Research has indicated that co-firing biomass can reduce the carbon footprint of coal-fired power plants, making it a viable option for countries aiming to meet their climate targets.

The co-firing combustion system involves burning two different materials simultaneously. Co-firing specifically refers to the simultaneous combustion of biomass fuels alongside coal in the same steam-generating unit. This can be achieved either by using existing coal combustion chambers or by retrofitting them to accommodate both coal and biomass[6]. This technology offers both environmental preservation and financial benefits.

In this study, the biomass used included rice husks, ironwood sawdust, and teak sawdust, which are abundantly available near the co-firing experiment site. These biomass materials were chosen for their local availability and potential to enhance combustion performance when mixed with coal. The selection of these materials aims to demonstrate the feasibility and benefits of using locally sourced biomass in co-firing processes. However, the practical implementation of biomass co-firing faces several challenges. Although policy encouragement for the large-scale use of biomass waste has been in place for several years, many raw biomass materials in Indonesia remain underutilized and are often disposed of through burning or landfilling[7]. This underutilization suggests a gap between policy and practice, emphasizing the need for improved infrastructure, greater awareness, and stronger incentives to promote the effective use of biomass resources.

A practical approach to rapidly increasing the use of biomass energy is to utilize biomass-coal mixtures in power plants originally designed to burn coal[8]. Understanding the thermal behavior of both coal and biomass is crucial, as it relates closely to their chemical properties[9,10]. When coal is heated to high temperatures in an inert, oxygen-free atmosphere, it decomposes, releasing water, tar, and gases. This process leaves behind a solid residue whose composition and properties vary depending on the heat treatment temperature. Typically, this decomposition occurs within the temperature range of 350-500°C[11].

To estimate the activation energy required for the thermal decomposition process, Thermo-Gravimetric Analysis (TGA) is employed. One of the techniques used in conjunction with TGA is Differential Scanning Calorimetry (DSC), which operates with a small sample weight, making it simple, precise, and quick for data collection[12]. DSC is a thermo-analytical technique that measures the difference in the amount of heat required to increase the temperature of a sample and a reference as a function of temperature. It provides an overview of the simultaneous thermal and mass changes occurring during heating. The TGA-DSC tool can be used to study the mass and thermal changes from the initiation of coal combustion to burnout. The data generated offers insights into the stages of spontaneous combustion of coal and helps anticipate the time of occurrence[13].

In the decomposition process using TGA/DSC, there is a relationship between the reduction of coal mass and the increase in temperature[14]. The instantaneous decomposition rate (weight loss rate), which reflects the weight loss and indicates the percentage of undecomposed coal, can be considered a function of the mass loss. This relationship holds if it is a function of temperature at a constant heating rate, with the heating rate serving as a parameter[15].

There is limited research on the potential of biomass and coal in Indonesia that discusses the use of TGA (Thermo-Gravimetric Analysis) and DTG-DSC (Differential Thermal Gravimetry-Differential Scanning Calorimetry) methods on the raw materials. Globally, the technologies commonly used include the Higher Heating Value (HHV) for calorific value measurement and Specific Fuel Consumption (SFC)[15,16]. Additionally, TG-DTA (Thermo-Gravimetric-Differential Thermal Analysis) and DTF (Drop Tube Furnace) methods are employed in lab-scale burning experiments to determine slagging and fouling tendencies in the samples used[16].

The plan to reduce the use of coal in power plants in Indonesia needs to be supported by various studies, including those on co-firing coal with renewable thermal-energy sources such as biomass. To date, there has been no comprehensive study on the use of different types of biomasses for co-firing in coal-fired power plants. Conducting such studies is crucial for understanding the potential and challenges of biomass co-firing and for optimizing its implementation to achieve sustainable energy goals.

2. Materials and Methods

This study aims to technically evaluate the feasibility of utilizing rice husk waste and sawdust for co-firing in a coal-fired power plant boiler with a capacity of 2x50 MW. The objectives include developing comprehensive recommendations for the efficient integration of biomass waste into the co-firing process. The study's findings are based on extensive field observations conducted over six weeks, during which various aspects were analyzed, such as combustion efficiency, emission reductions, and operational impacts on the power plant.

The methodology for implementing the study on the utilization of biomass waste for power plant fuel is divided into the following stages:

2.1 Data Collection and Power Plant Specification

- Gather detailed operational data and technical specifications of the 2x50 MW coal-fired power plant.
- This includes information on the plant's current fuel usage, combustion systems, emission controls, and overall efficiency.

2.2. Fuel Characterization Testing:

- Conduct comprehensive tests to characterize the biomass waste, including rice husk and sawdust.
- Combustion Air Requirement: Measure the theoretical and actual air needed for complete combustion of biomass-coal mixtures.
- Calorific Value: Determine the energy content of the biomass materials compared to coal to assess the impact on overall fuel efficiency.
- Ignition Point: Identify the temperature at which each type of biomass ignites to understand how it influences the combustion process in the boiler.
- Thermo-Gravimetric Analysis (TGA): Perform TGA to analyse the thermal stability and decomposition characteristics of the biomass fuels. This includes studying the weight loss as a function of temperature to predict the combustion behaviour of the biomass.

The analysis of the properties of the coal and rice husk mixture involves several key parameters, including the ash melting point and combustion temperature. These properties are anticipated to exhibit non-linear behavior with varying proportions of biomass in the coal mixture. Additional characteristics, such as calorific value, proximate analysis, and ultimate analysis, will be evaluated based on the specific ratios of rice husk mixed with coal.

Moreover, tests will be conducted to determine the effectiveness of converting 1%, 3%, and 5% of coal to rice husk, teak, ironwood, and sawdust mixtures. This comprehensive analysis aims to provide insights into the feasibility and efficiency of utilizing different biomass types in coal-fired power plants, highlighting the potential benefits and challenges associated with various biomass-coal ratios.

The behavior of materials under heating can be thoroughly analyzed using a Simultaneous Thermal Analysis (STA) tool. This tool combines Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) to measure mass changes and heat flow as functions of temperature and time under controlled conditions. The simultaneous measurement of these two material properties enhances productivity and simplifies the interpretation of results.

The data obtained from using the STA-TGA/DSC tool provides detailed information on the endothermic and exothermic events that occur during material mass loss (such as during degradation) and in the absence of mass loss (such as during melting and crystallization). This combined analysis allows for the correlation of mass loss with thermal transitions, offering comprehensive insights into material behavior under thermal conditions.

Understanding these parameters and results is crucial for determining the thermal stability, decomposition kinetics, phase transitions, and other thermal properties of materials. This information is essential for optimizing material performance in various applications, such as in the co-firing of biomass and coal in power plants, where thermal stability and decomposition characteristics significantly impact efficiency and emissions.

The TGA-DSC system monitors and records the relative mass loss, rate of relative mass loss, relative heat flow, and rate of relative heat flow in air as a function of temperature[16]. Additionally, the first derivatives with respect to time, dTG (DT/dt) and dDSC (dDSC/dt), are also tracked. This methodology has gained recognition as an excellent approach for examining the combustion properties of various solid materials. By continuously monitoring and recording the sample's weight loss and weight loss rates under dynamic conditions (either as a function of time or temperature), the TGA-DSC system provides a comprehensive analysis of the material's thermal behavior. Relevant parameters, such as the onset of decomposition, peak degradation temperatures, and heat flow characteristics, can be determined from the thermogram.

These insights are depicted in Fig. 1. This approach is particularly valuable for studying the combustion properties of biomass and coal mixtures, as it allows for a detailed understanding of the thermal stability, decomposition kinetics, and energy release patterns of the materials involved. Such information is crucial for optimizing the co-firing process in power plants to enhance efficiency and reduce emissions.

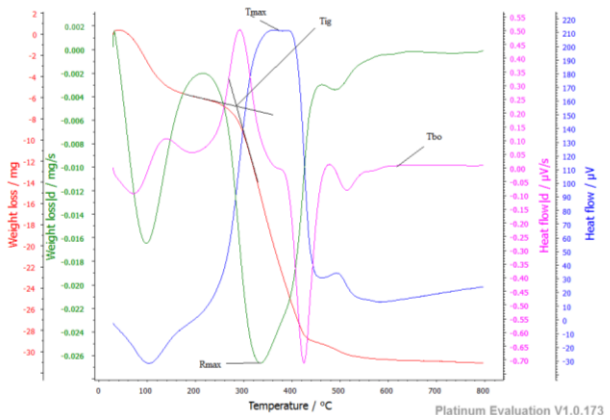


Fig. 1: TGA-DSC test result parameters.

Figure 1 shows the combined results of Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC), both of which are used to study the thermal properties of materials. Here's a detailed breakdown of the parameters and curves shown in the graph:

2.3 TGA (Thermogravimetric Analysis)

- Weight Loss (TG curve): Represented in green, this curve illustrates the change in weight of the sample as a function of temperature. The y-axis on the left side of the graph indicates the weight loss in mass (mg).
- Derivative Weight Loss (DTG curve): Shown in red, this curve represents the rate of weight loss (the derivative of the TG curve) as a function of temperature. It helps to more clearly identify the temperatures at which significant weight loss events occur.

2.4 DSC (Differential Scanning Calorimetry)

- Heat Flow (DSC curve): Represented in blue, this curve illustrates the amount of heat absorbed or released by the sample as a function of temperature. The y-axis on the right side of the graph shows the heat flow in units of µV (thermal voltage), or the temperature difference between a sample and reference, it can be converted into a heat flux difference in mW (or mJ/s).
- Derivative Heat Flow (dDSC curve): This curve shows the rate of change of heat flow and helps in identifying specific thermal events such as melting, crystallization, or phase transitions.

2.5 Key Insights from the Graph

- Weight Loss Events: The green TG and DTG curves help identify specific temperatures at which the material loses weight, indicating dehydration, decomposition, volatilization, or other mass loss processes.
- Heat Flow Events: The blue DSC and dDSC curves highlight exothermic or endothermic events, such as oxidation, reduction, melting, and crystallization, or glass transitions providing insights into the thermal stability and transitions of the material.
- Derivative Weight Loss: The red DTG curve helps pinpoint the exact temperatures at which weight loss events occur, making it easier to identify multiple overlapping events.

Correlation of Mass and Thermal Changes: By analyzing both TGA and DSC data, one can correlate mass loss events with corresponding thermal events, offering a comprehensive understanding of the material's behavior under thermal conditions.

2.6 Practical Applications

This combined TGA-DSC analysis is essential for optimizing the co-firing process in power plants, as it helps in:

- Identifying Optimal Biomass Mixtures: Understanding how different biomass materials behave when mixed with coal.
- Enhancing Combustion Efficiency: Determining the best operating conditions to maximize combustion efficiency and minimize emissions.
- Ensuring Material Compatibility: Ensuring that the selected biomass materials are compatible with existing combustion systems and do not lead to operational issues like fouling or corrosion.

These insights are crucial for the effective implementation of biomass co-firing in coal-fired power plants, contributing to reduced greenhouse gas emissions and enhanced utilization of renewable energy sources.

2.7 Key Parameters

In this study, the TGA-DSC test focused on evaluating coal and biomass materials sourced from rice husks, ironwood sawdust and teak wood sawdust. By analyzing these curves and parameters, we can gain insights into the thermal stability, composition, and phase transitions of the materials being studied. Various parameters of the TGA-DSC profile can be obtained[17]:

- Tig (°C): The initial combustion temperature at which the weight loss curve (TGA) of the starting coal combustion crosses the steep weight loss curve. This is indicated by a black line in the baseline of the DSC curve.
- Tmax (°C): The temperature at which the material reaches its maximum melting rate, indicated by a peak in the DSC curve.
- Tbo/Boiling Temperature (°C): The temperature at which the heat flow rate is zero at the end of the combustion process (dDSC), often indicated by a significant weight loss in the TGA curve.
- Rmax (mg/s): The maximum rate of weight loss against time (dDTG) at Tmax.
- Onset/offset point: The initiation and termination times of the oxidation reaction between carbon and oxygen in TGA-DSC analysis are determined utilizing LINSEIS High-Pressure STA (Simultaneous Thermal Analysis) TG-DTA/DSC (thermogravimetry/ differential thermal analysis/ differential scanning calorimetry) with the following procedures:
  - The furnace is opened, and a sample is weighed and placed in the crucible.
  - Next, the furnace is closed again.
  - Configure the temperature program with the following parameters:
    - Rate : 10°C/min
    - Temperature : 900°C
    - Dwelled time : 2 min.
  - The appliance is shut off after cooling with a flow rate (rate) of 10°C/min to a temperature of 50°C and holding the heat for 2 minutes at a temperature of 900°C.

Figure 2 shows the TGA/DSC apparatus used for studying the nature of coal combustion.

Fig. 2: High pressure LINSEIS STA TG-DTA / DSC.

3. Result and Discussion

3.1 Combustion Air Requirement

The need for combustion air is strongly influenced by the components in the fuel. Generally, coal contains higher carbon elements than biomass. Biomass has a higher H/C ratio and O/C ratio than coal[18], which also determines the theoretical air requirement necessary to completely burn the fuel. For complete combustion, the air supply is typically 20-30% higher than the theoretical requirement. In cases of excessive air supply, combustion heat is absorbed by the surplus air, leading to increased heat losses due to the exhaust gases emitted from the chimney. Adjusting the supplied air content is essential when co-firing biomass with coal[19].

Therefore, measuring the O_2 content in the exhaust gases and maintaining it at an optimal level is crucial. Complete combustion requires sufficient air to fully oxidize the fuel, and the air requirement depends on the fuel's C, H, N, and S composition[20]. The following figure summarizes the fuel requirements for each type of fuel. The tabulated data reveals that, in a theoretical context, coal requires more air for complete combustion than rice husks or sawdust. This discrepancy is due to coal's higher carbon content compared to biomass[21]. Introducing biomass into the combustion process with coal reduces the required air volume for efficient combustion. Practically, this means adjustments must be made to the air supply in the boiler system during co-firing to prevent an excess of combustion air, which would decrease boiler efficiency.

Assuming the air supplied is the same as the air used with coal fuel (O_2 content in flue gas 6.63% and excess air 44.38%), excess air due to surplus air supply and thermal losses due to exhaust gas can be calculated. Calculation results for co-firing using rice husk, sawdust Ironwood, and teak sawdust, are shown in Fig. 3.

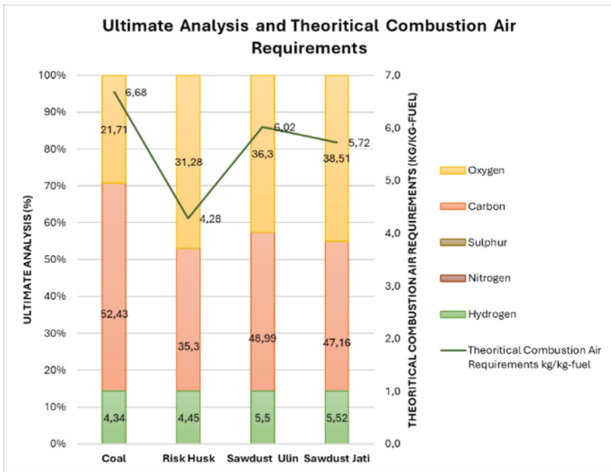
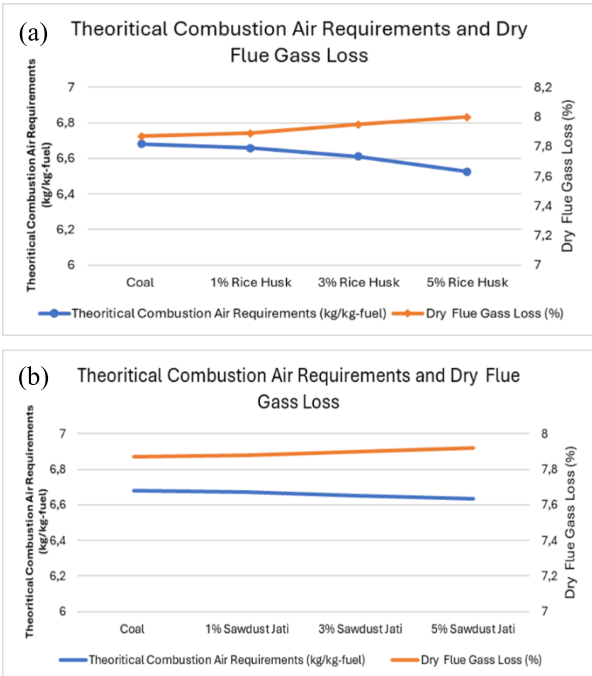


Fig. 3: Ultimate analysis and theoretical combustion air requirements.

In Fig. 3, a comparison of ultimate analysis and theoretical combustion air requirements is presented, showing the content of carbon, oxygen, hydrogen, sulfur, and nitrogen from coal, rice husk, Ironwood sawdust, and teak sawdust.

As shown in Fig. 4(a), for every 1% addition of rice husk into the fuel, the combustion air requirement is reduced by 0.024 kg/kg-fuel. If the air supply remains constant, the excess air will result in a 0.02% decrease in efficiency due to exhaust loss.

Regarding sawdust, Fig. 4(b) and 4(c) illustrate that the addition of 1% sawdust reduces the need for combustion air by 0.003 kg/kg fuel for ironwood and 0.009 kg/kg fuel for teak. The increased exhaust gas losses that occur when the volume of air supplied is not lowered are approximately 0.01% for every 1% addition of teak sawdust or ironwood sawdust.



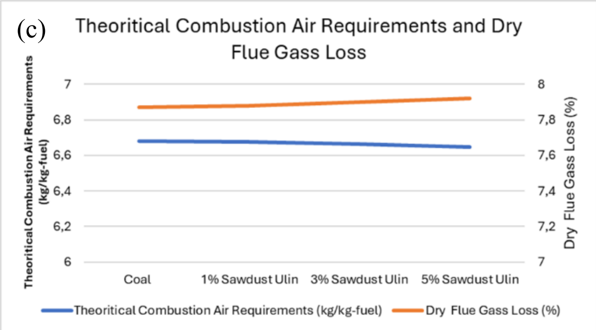


Fig. 4: (a) Theoretical combustion air requirement and dry flue gas loss due to co-firing (rice husk) (b) theoretical combustion air requirement and dry flue gas loss due to co-firing (ironwood sawdust) (c) theoretical combustion air requirement and dry flue gas loss due to co-firing (teak sawdust).

To avoid excessive air supply, it is necessary to control the O_2 content in the exhaust gas. By doing so, boiler efficiency can be maintained, and exhaust gas losses can be minimized due to the reduced combustion air volume[22]. This careful management of combustion air is essential to optimize the efficiency of the boiler and reduce unnecessary thermal losses.

3.2 Calorific Value Analysis

Biomass generally exhibits a lower calorific value compared to coal, primarily due to its lower fixed carbon content. Additionally, the water content, or moisture, in the fuel plays a significant role in determining its calorific value. Figure 5 illustrates the fixed carbon content, moisture content, and calorific value of coal and various types of biomasses, including rice husk, ironwood sawdust, and teak sawdust. As depicted in the figure, there is a clear correlation between fixed carbon content and calorific value: as the fixed carbon content decreases, so does the calorific value of the fuel. This trend is consistent across the different types of biomasses tested.

Interestingly, despite the noticeable disparity in fixed carbon content between ironwood sawdust and teak sawdust, their calorific values are relatively similar. This can be attributed to the difference in moisture content between the two types of sawdust. The lower fixed carbon content in teak sawdust is effectively balanced by its higher moisture content compared to ironwood sawdust. This balancing effect indicates that while fixed carbon content is a key factor in determining calorific value, moisture content also plays a crucial role[23,24].

The overall energy content of biomass fuels is influenced not only by their carbon content but also by their moisture levels, which can significantly impact their practical use in combustion processes. This understanding is essential for optimizing biomass utilization in co-firing applications and ensuring efficient energy production.

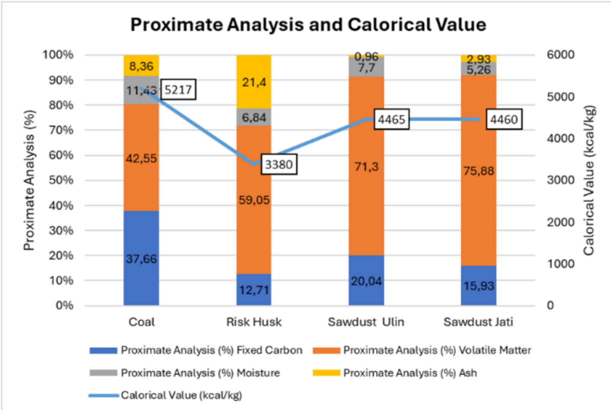
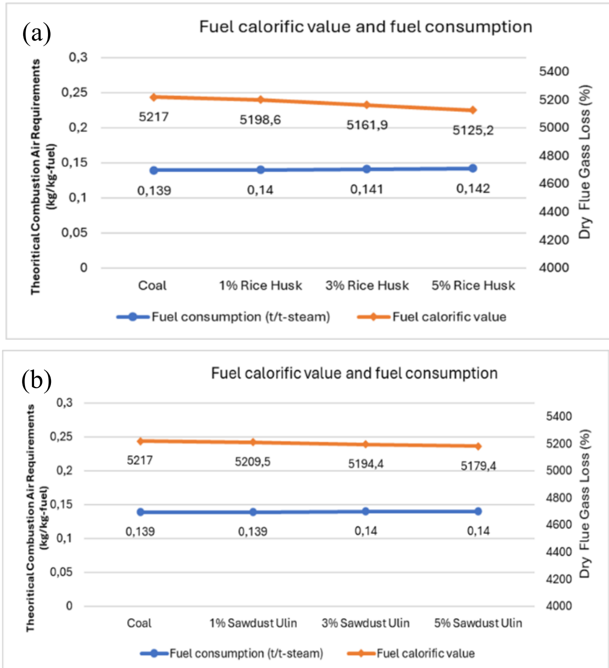


Fig. 5: Fix carbon content, moisture, and calorific value of fuel.

Figure 6 illustrates the changes in calorific value resulting from the addition of biomass to coal. The data clearly shows a reduction in the calorific value as the proportion of biomass mixed with coal increases. Specifically, the inclusion of rice husks at a 1% ratio reduces the calorific value of the coal by 19 kcal/kg. Similarly, the addition of 1% ironwood sawdust decreases the calorific value by 7.5 kcal/kg, while adding 1% teak sawdust results in a slightly greater reduction of 7.6 kcal/kg. This decrease in calorific value due to biomass incorporation necessitates an adjustment in the fuel quantity required to generate the same amount of steam. For instance, adding 1% rice husk to coal increases the fuel requirement by 1 kg per ton of steam produced. In contrast, the addition of 1% ironwood sawdust or teak sawdust requires a lesser increase in fuel, amounting to 0.2 kg per ton of steam.



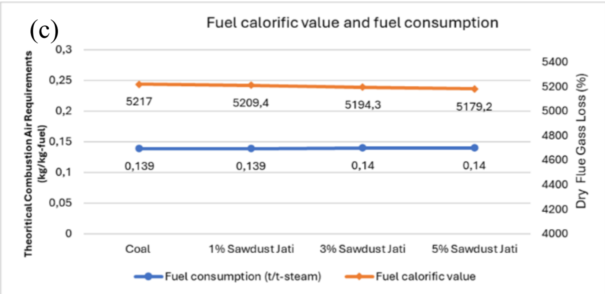


Fig. 6: (a) Fuel calorific value and consumption per ton of steam (co-firing rice husk) (b) fuel calorific value and consumption per ton of steam (co-firing sawdust ironwood) (c) fuel calorific value and consumption per ton of steam (co-firing teak sawdust).

Therefore, the practical implications of using biomass in co-firing with coal involve not only a reduction in calorific value but also a proportional increase in fuel consumption to maintain steam production efficiency. This adjustment must be considered when optimizing fuel blends for power generation to ensure that the overall performance of the combustion system remains efficient and effective.

3.3 Ignition Point

The ease of fuel combustion is indicated by the ignition point, which is influenced by the concentration of volatile matter (VM) within the fuel. A lower ignition point typically corresponds to a higher volatile matter content. Biomass generally has a higher VM content compared to coal. As shown in Fig. 7, the volatile matter content of rice husk is 17.5% higher than that of coal, with rice husk having a VM content of 42.55%. As the VM content increases, the ignition points of the fuel decreases. For example, coal exhibits an ignition point of 443°C. In contrast, ironwood sawdust, rice husk, and teak sawdust have significantly lower ignition points of 312°C, 324°C, and 318°C, respectively. This indicates that the addition of biomass to coal reduces the fuel's ignition point, making the fuel mixture ignite more readily and burn faster. This enhanced flammability due to the lower ignition point of the biomass is beneficial for improving the efficiency of combustion processes.

Figure 7 illustrates this effect, demonstrating the impact of biomass addition on the overall ignition characteristics of the fuel mixture. By understanding and leveraging the combustion properties of biomass, such as its higher volatile matter content and lower ignition point, it is possible to optimize the co-firing process in coal-fired power plants. This can lead to more efficient and environmentally friendly energy production, highlighting the potential benefits of integrating biomass with traditional coal fuel.

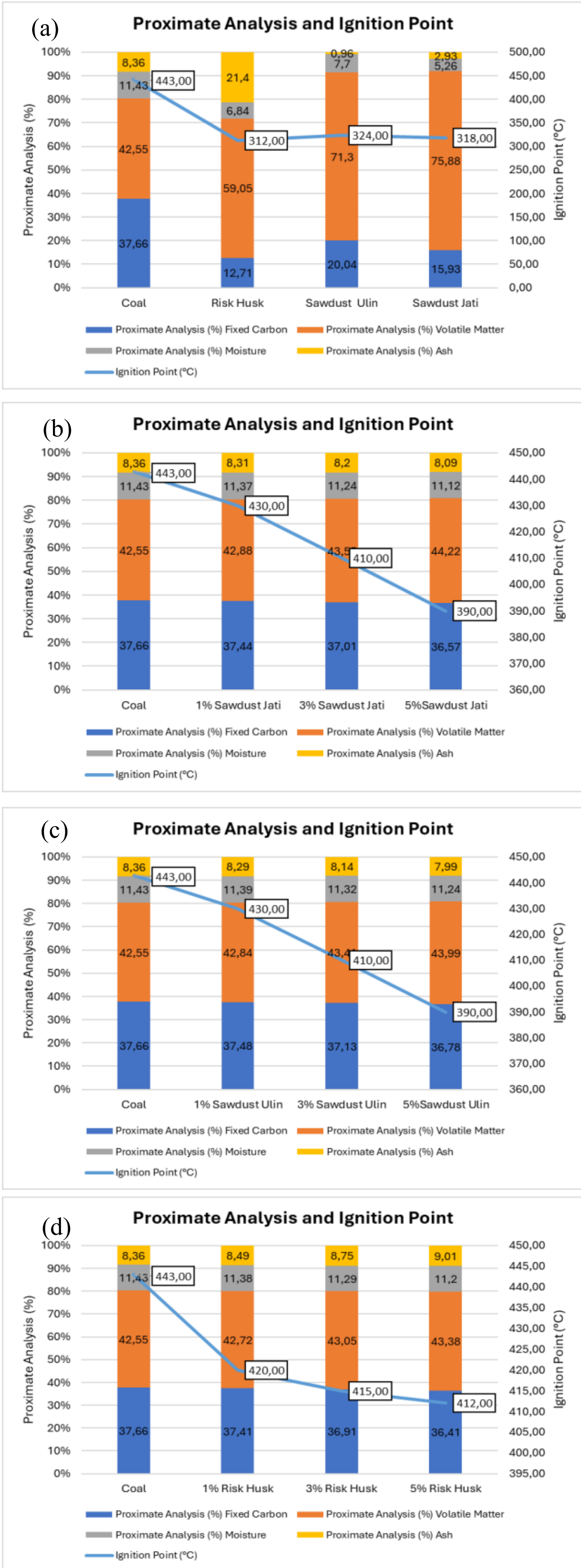


Fig. 7: (a) Proximate analysis and fuel flash point (b) proximate and flash point analysis of coal + rice husk mixed fuel (c) proximate and flash point analysis of coal + ironwood sawdust mixed fuel (d) proximate and flash point analysis of coal + teak sawdust mixed fuel.

3.4 Thermogravimetry analysis

Thermogravimetric analysis (TGA) of coal samples, rice husks, teak sawdust, and ironwood sawdust was conducted using a Simultaneous Thermal Analyzer (STA TGA/DSC) to understand the thermal behavior of coal and biomass during heating and combustion processes. The measurement data obtained from the STA are organized into mass change curves (TGA) and heat flow curves (DSC) as functions of temperature and time. These curves provide critical information on the endothermic and exothermic events occurring during material mass loss (e.g., decomposition or combustion) and events occurring without mass loss (e.g., melting and crystallization)[25,26). Differential Scanning Calorimetry (DSC) measures the difference in energy input between a sample and a reference material at specified temperatures. This method quantifies energy differences that are directly proportional to the physical or chemical changes in the sample. By applying this approach, DSC can identify transitions such as phase changes and reaction kinetics[27).

Thermogravimetric analysis (TGA) relies on monitoring sample mass loss at various temperatures during controlled heating. This technique involves heating a specified mass of the sample according to a predetermined temperature program and plotting the mass change against temperature or time, resulting in thermo-gravimetric (TG) curves. The derivative of the TG curve, known as the differential thermo-gravimetric (DTG) curve, highlights the rates of mass loss and provides detailed insights into the thermal decomposition process[27).

The combination of TGA and DSC data offers a comprehensive understanding of the thermal stability, decomposition kinetics, and phase transitions of the materials studied. This integrated approach is essential for optimizing the co-firing process in coal-fired power plants, enabling the effective utilization of biomass alongside coal for improved efficiency and reduced environmental impact.

There are four key combustion characteristics used to interpret the combustion profile from TGA analysis results:

a. Initiation Temperature (Tig): The temperature at which the material begins to burn and weight loss starts.
b. Starting Temperature: The point where the mass loss rate increases significantly due to the onset of coal burning.
c. Peak Temperature (Tmax): The maximum temperature reached during combustion, corresponding to the highest rate of weight loss (Rmax).
d. Burnout Temperature (Tbo): The temperature at which the weight of the material becomes constant, and the rate of heat generation drops to zero, indicating the end of combustion[28).

Among these characteristics, temperature exhibits a clear correlation with weight/mass changes. Additionally, an onset/offset point is discernible, signifying the initiation and cessation of the carbon-oxygen oxidation reaction.

The TG-DSC curves for coal, biomass, and their mixtures were obtained under ambient air conditions. Below 100°C, an endothermic event is observed, requiring heat to eliminate moisture content. As the temperature increases, a gradual reaction with oxygen occurs, leading to the release of several volatile light fractions around 200°C. The mass continues to decrease until the initial temperature (Tig) is reached, marking the point where the material begins to ignite. Tig, or initiation temperature, is identified by the intersection of the tangential line with the TG curve, where significant mass loss begins. This is due to the devolatilization of volatile matter, initiating the combustion process. Tig is a crucial parameter for furnace design and process start-up. When coal is fed into a furnace at a temperature below Tig, it will not ignite[29). Tig is also the lowest temperature at which solid fuels begin to ignite in the air without the aid of an external ignition source[30).

Understanding these combustion characteristics through TGA-DSC analysis is vital for optimizing fuel mixtures in co-firing applications, ensuring efficient and stable combustion while minimizing environmental impact.

The thermal process continues until it reaches a temperature where coal and biomass undergo the decomposition of hydrocarbon bonds. Between 200°C and 400°C, known as the active pyrolysis zone, the degradation of hydrocarbon bonds occurs at a faster rate. This is an exothermic event, indicated by a rapid decline in mass, until it reaches the maximum combustion rate (Rmax). The mass loss against time is measured in mg/s, and a high Rmax value suggests that the material is easier to burn or has a high combustion efficiency[31).

During exothermic reactions, a certain amount of heat is released due to the thermal degradation of hydrocarbon bonds into combustible gases. The DSC curve identifies the initial and final temperatures of carbon and oxygen oxidation reactions, marked as onset and offset points. Tmax represents the maximum temperature linked to combustion reactivity. This indicates the capacity of coal or biomass to undergo low-temperature oxidation, potentially resulting in spontaneous combustion. A higher Tmax value signifies greater material reactivity, indicating a heightened tendency for self-ignition.

Understanding these thermal behaviors through TGA-DSC analysis is crucial for optimizing the co-firing process. By identifying the key thermal events and their respective temperatures, we can better manage combustion efficiency and safety in coal-fired power plants using biomass.

After reaching the maximum temperature, the combustion process continues with the burning of charcoal within a temperature range of 400-500°C. The thermal decomposition of charcoal occurs at a slower rate of mass loss compared to the decomposition of volatile matter during the active pyrolysis phase (200-400°C). During this phase, the thermal events associated with charcoal burning release heat, which is the activation energy from the heating reaction. This released heat contributes to an increase in the calorific value of the material. The heat released during these thermal events is reflected in the DSC curve as an enthalpy value[32]. This value indicates the amount of heat absorbed or released during the phase transitions and chemical reactions occurring within the sample. The slower rate of mass loss during charcoal combustion, compared to the more rapid decline during volatile matter decomposition, signifies a shift from active pyrolysis to the more stable combustion of fixed carbon components in the charcoal.

Understanding these thermal processes is crucial for optimizing the co-firing of biomass with coal in power plants. By analyzing the TGA-DSC data, we can gain insights into the thermal stability, decomposition kinetics, and heat release characteristics of different fuel mixtures. This knowledge helps in designing efficient combustion systems, managing fuel blends, and improving overall boiler efficiency while minimizing environmental impacts.

3.4.1 DTG-DSC test results of Coal Samples, Rice Husk, Sawdust Teak, and Sawdust Ironwood

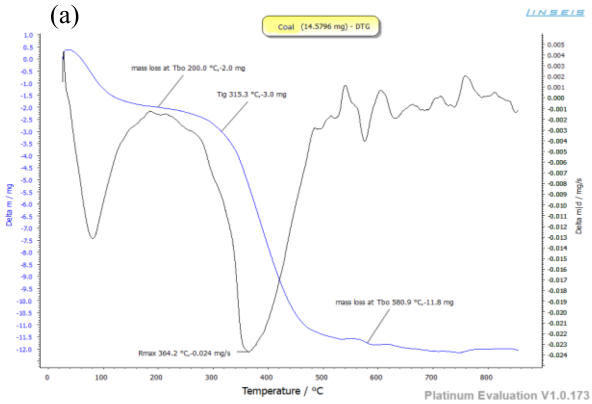
DTG-DSC test results for coal, rice husk, teak sawdust, and ironwood sawdust samples are shown in Fig. 8 and Fig. 9, with the summary provided in Table 1 as follows:

Table 1. Resume sample DTG-DSC testing data.

Sample	**Weight (mg)**	**Mass Loss at Tig**			**Rmax mg/s**	
		Tig (°C)	**mg**	**%**		
Coal	14,57960	310,7	2,9	19,9	0,024	
Rice Husk	18,46730	275.4	1,4	7,6	0,042	
Sawdust Teak	9,82106	280,5	0,9	9,2	0,026	
Sawdust Ironwood	11,47540	280	0,9	7,8	0,029	
Sample	**Tbo (°C)**	**Mass Loss at Tbo**		**Onset Point**		
		mg	**%**	**(°C)**	**Time (min)**	
Coal	731,1	12,1	83	300	13	
Rice Husk	713,6	10,3	55,8	281,6	12	
Sawdust Teak	515,1	7,3	74,3	394,7	17	
Sawdust Ironwood	671,9	8,0	69,7	287,7	11	
Sample	**Offset Point**		**Point of Reaction**		**T max (°C)**	**Enthalpy (J/g)**
	(°C)	**Time (min)**	**(°C)**	**Time (min)**		
Coal	492,8	23	347,3	15	390,5	16.233,69
Rice Husk	524,7	25	312,6	14	347,2	6.353,36
Sawdust Teak	460,4	21	414,5	18	431,4	7.264,87
Sawdust Ironwood	527,9	22	336	13	358,8	5.392,17

Among the samples of coal, rice husk, teak wood, and ironwood, the highest Tig value is found in coal at 310.7°C with the greatest mass loss of 19.9%. This means that at these temperatures, the coal will not burn. The lowest Tig value is for rice husks (275.4°C), while teak and ironwood begin to burn at similar temperatures (280.5°C and 280.0°C, respectively). The percentage of mass loss for rice husk and ironwood were 7.6% and 7.8%, respectively, while teak wood exhibited a mass loss of 9.2%.

(a)



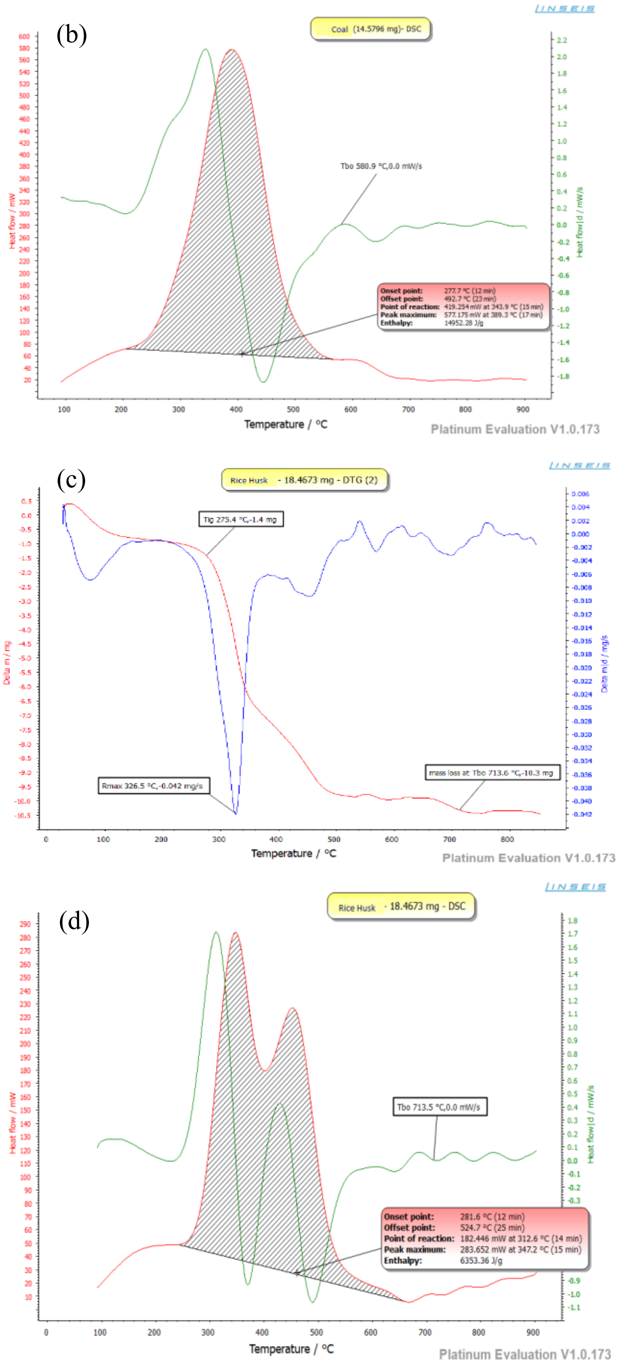
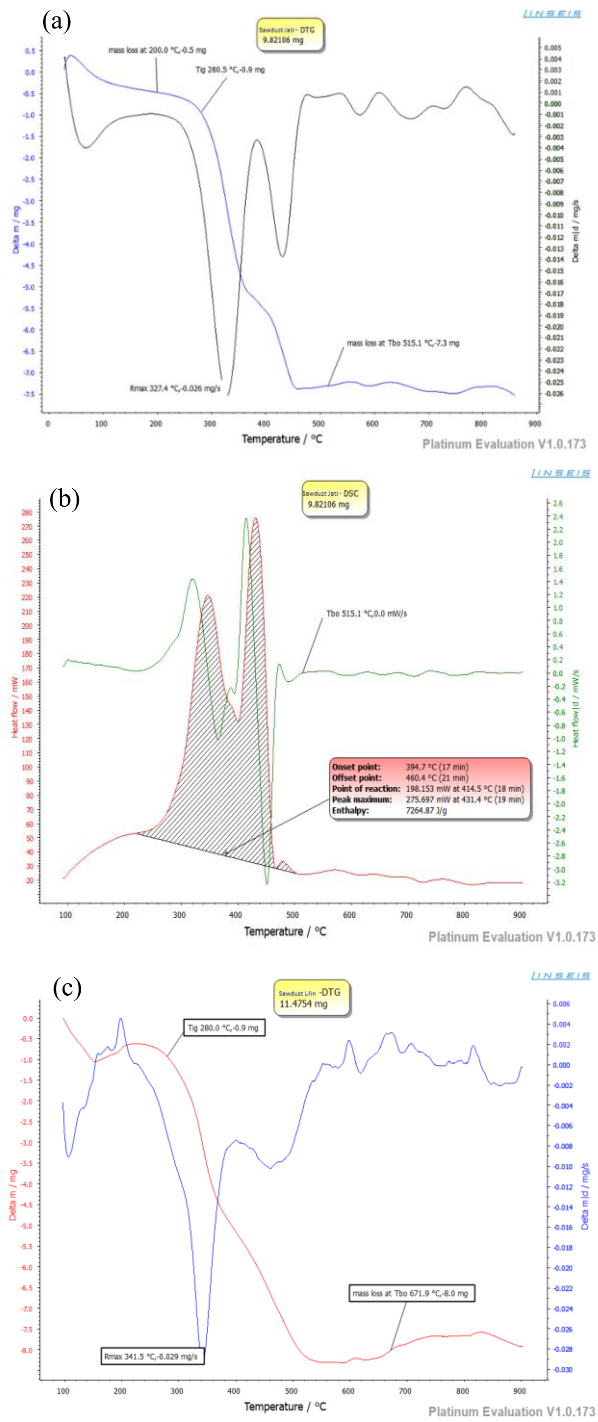


Fig. 8: (a) Coal sample DTG curve (b) coal sample DSV curve **(c)** DTG curve of rice husk sample (d) DSC curve of rice husk sample.



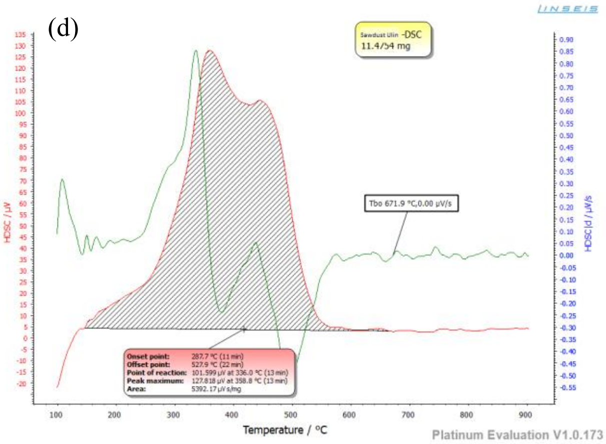


Fig. 9: (a) DTG curve teak sawdust sample (b) DSC curve teak sawdust sample (c) DTG curve - sample sawdust ironwood (d) DSC curve - sample sawdust ironwood Tmax of coal at 390.5°C, teak wood is highest at 414.5°C while rice husk is lowest at 281.6°C. Ironwood has the lowest enthalpy while coal is the highest.

The DTG curve shows that rice husk has the highest combustion efficiency with an Rmax of 0.042 mg/s. The oxidation reaction of carbon and oxygen in coal begins at 300°C and lasts for 10 minutes, starting at minute 13 (onset point) and ending at a temperature of 492.8°C at minute 23 (offset point). The peak temperature of the combustion reaction between carbon and oxygen in coal (reaction point) occurs at minute 15, with a temperature of 347.3°C.

The burn-off temperature (Tbo) reflects the characteristics of the final combustion of charcoal where the heat flow rate (Rmax) is zero. Coal Tbo occurs at a temperature of 731.1°C with a mass loss of 83%. It can be assumed that the remaining 17% is Ash[33].

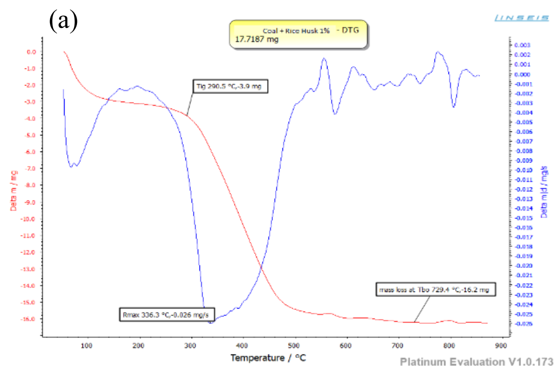
3.4.2 DTG-DSC test results of coal and rice husk mixture samples

The results of the DTG-DSC test for 1%, 3%, and 5% rice husk mixture samples are shown in Figures 10 and 11. The summary of the DTG-DSC data for coal and rice husk mixtures can be seen in Table 2.

Table 2. Resume testing data DTG-DSC coal + rice husks.

Sample	**Weight (mg)**	**Mass Loss at Tig**			**Rmax mg/s**	
		Tig (°C)	**mg**	**%**		
Coal + Rice Husk 1%	17,71870	290,5	3,9	22,0	0,026	
Coal + Rice Husk 3%	12,35930	301,3	2,8	22,7	0,022	
Coal + Rice Husk 5%	10,36730	319,5	2,8	27,0	0,021	
Sample	**Tbo (°C)**	**Mass Loss at Tbo**		**Onset Point**		
		mg	**%**	**(°C)**	**Time (min)**	
Coal + Rice Husk 1%	729,4	16,2	91,4	264,3	11	
Coal + Rice Husk 3%	587,9	11,2	92,2	292,6	13	
Coal + Rice Husk 5%	727,5	10,1	97,4	303,5	12	
Sample	**Onset Point**		**Offset Point**		**T max (°C)**	**Enthalpy (J/g)**
	(°C)	**Time (min)**	**(°C)**	**Time (min)**		
Coal + Rice Husk 1%	500,4	23	318,1	13	407,6	18.178,54
Coal + Rice Husk 3%	488,2	23	335,1	14	372,7	17.899,21
Coal + Rice Husk 5%	496,1	21	351,9	14	397,3	20.731,84

The DTG curve for the coal + 1% rice husk mixture shows that the sample begins to burn at a temperature of 290.5°C (Tig). The higher the concentration of rice husk added, the higher the Tig, and the greater the mass loss. An increase in rice husk concentration also results in higher onset-offset points, reaction points, and activation energy (enthalpy)[34]. The highest combustion efficiency is obtained from coal + 1% rice husk, which has the greatest Rmax value of 0.026 mg/s. Combustion efficiency decreases as the concentration of rice husk increases[35]. As shown in Fig. 10, the maximum temperature associated with the reactivity of combustion, which can lead to spontaneous combustion, shows that coal + 1% rice husk has the highest tendency for spontaneous combustion compared to coal + 3% and 5% rice husk mixtures[36].



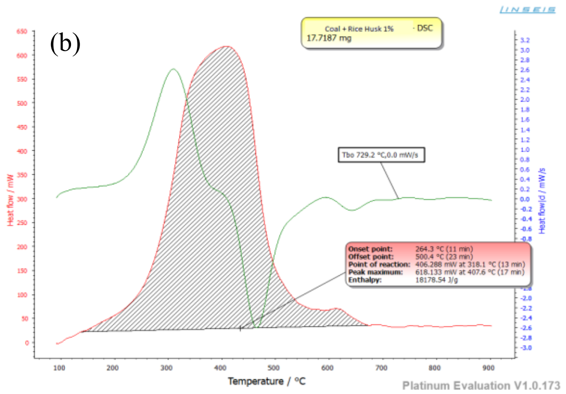
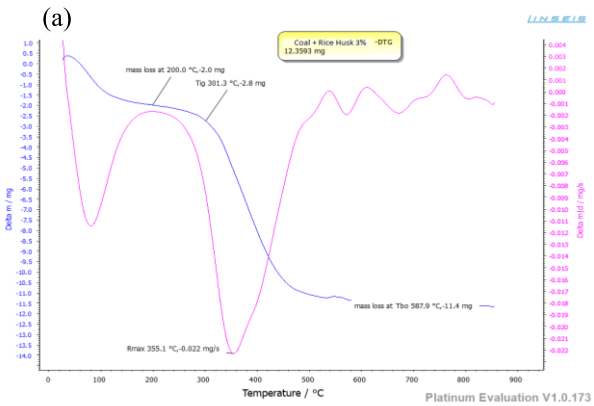
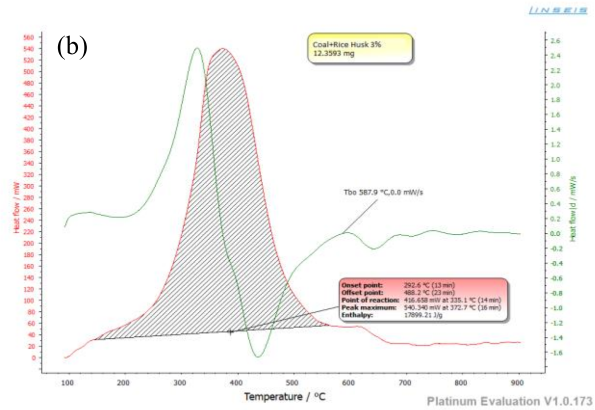


Fig. 10: (a) Coal TGA curve+rice husk 1% (b) curve DSC coal+rice husk 1%.

As visualized in Fig. 11, the coal + 3% rice husk mixture experienced burning at the lowest temperature compared to coal + 1% and coal + 5% rice husk mixtures. The largest weight loss was observed in the coal + 5% rice husk mixture, which had the lowest ash content of 2.6% (97.4% mass loss).





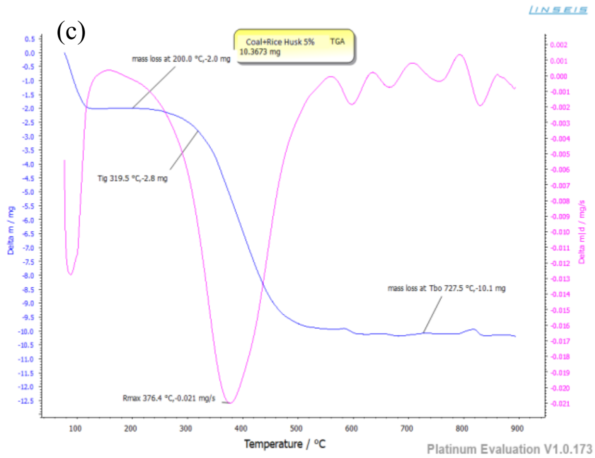


Fig. 11: (a) Curve TGA coal + rice husk 3% (b) curve DSC coal+rice husk 3% (c) curve DSC coal + rice husk 5%.

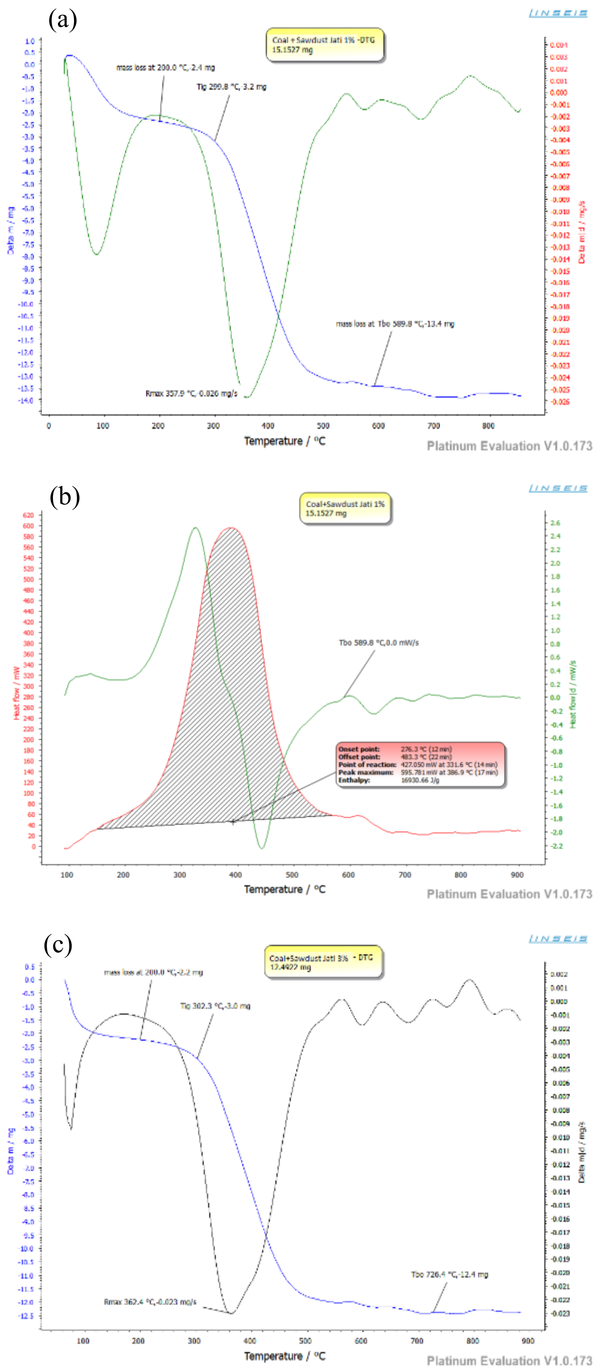
Table 3. Resume testing data DTG-DSC coal + sawdust teak.

Sample	**Weight (mg)**	**Mass Loss at Tig**			**Rmax mg/s**	
		Tig (°C)	**mg**	**%**		
Coal + Sawdust Teak 1%	15,15270	299,8	3,2	21,1	0,026	
Coal + Sawdust Teak 3%	12,49220	302,3	3,0	24,0	0,023	
Coal + Sawdust Teak 5%	13,73200	200,0	2,2	16,0	0,025	
Sample	**Tbo (°C)**	**Mass Loss at Tbo**		**Onset Point**		
		mg	**%**	**(°C)**	**Time (min)**	
Coal + Sawdust Teak 1%	598,8	13,4	88,4	276,3	12	
Coal + Sawdust Teak 3%	726,4	12,4	99,3	289,6	12	
Coal + Sawdust Teak 5%	726,3	13,4	97,6	288,9	13	
Sample	**Offset Point**		**Point of Reaction**		**T max (°C)**	**Enthalpy (J/g)**
	(°C)	**Time (min)**	**(°C)**	**Time (min)**		
Coal + Sawdust Teak 1%	483,3	22	331,6	14	386,9	16.930,66
Coal + Sawdust Teak 3%	499,8	22	337,3	14	397,8	20.564,39
Coal + Sawdust Teak 5%	491,5	23	339,5	15	388,1	19.852,47

3.4.3 DTG-DSC test results mixed samples of coal and teak sawdust

DTG-DSC test results for mixed samples of coal with teak sawdust of 1%, 3%, and 5% are shown in Fig. 12-13, while the summary data of DTG-DSC mixed coal and teak sawdust can be seen in Table 3.

The DTG-DSC curve of coal and teak wood samples showed a mixture of coal + teak wood was 5% faster to ignite with Tig at 200.0°C with a mass loss of 16.0%. A mixture that has a high combustion efficiency or is easier to burn is a mixture of coal + rice husk 1% with Rmax 0.026 mg/s.



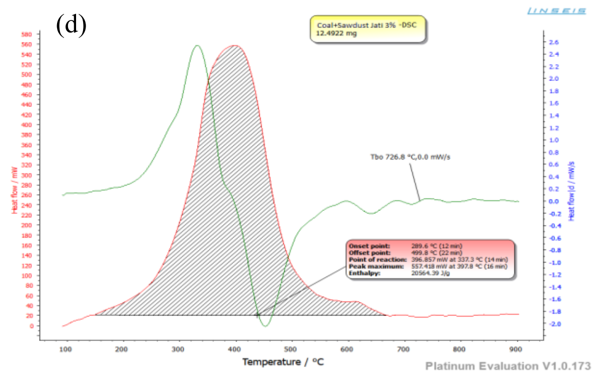


Fig. 12: (a) Curve DTG coal + teak 1% (b) curve DSC coal + teak 1% (c) curve DSC coal + Teak 3% (d) curve DSC coal + Teak 3%.

The DSC curve shows that as more teak sawdust is added, the onset and offset points, as well as the reaction point, increase in temperature. In the coal + 1% rice husk mixture, the highest Tmax was observed at 407.6°C, while the highest enthalpy was recorded in the coal + 5% teak sawdust mixture.

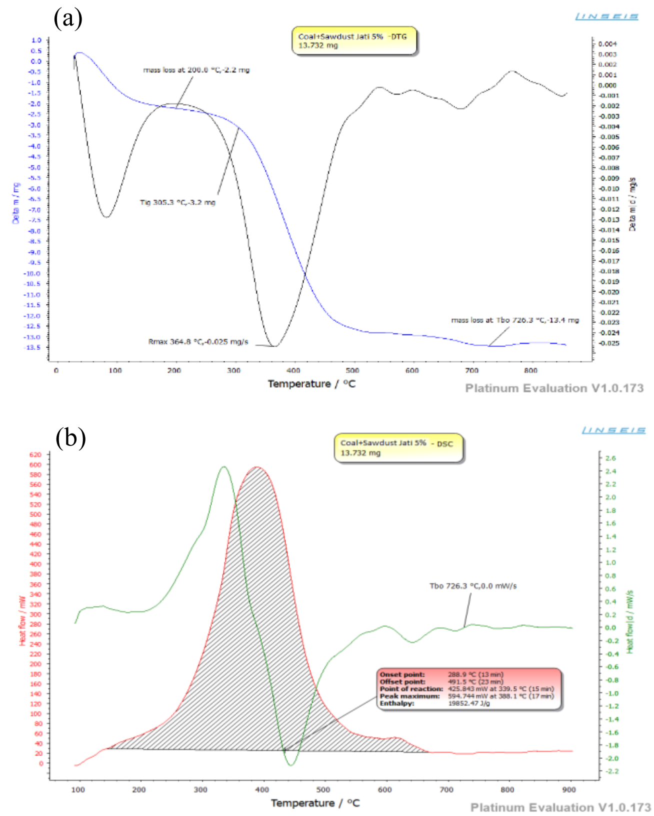


Fig. 13: (a) Curve DTG coal + teak 5% (b) curve DSC coal + teak 5%.

Ash content, as a residue from the combustion of charcoal, is determined at Tbo, where the rate of heat reduction reaches 0.0 mW/s. The ash content for the mixture of coal + 5% teak wood is 8.6%, 7.8%, and 2.6% respectively.

3.4.4. DTG-DSC test results of coal and Ironwood mixture samples

The DTG-DSC test results for coal mixture samples with 1%, 3%, and 5% ironwood sawdust are shown in Fig. 14, while the summary of the DTG-DSC data for the coal and ironwood sawdust mixtures can be seen in Table 4.

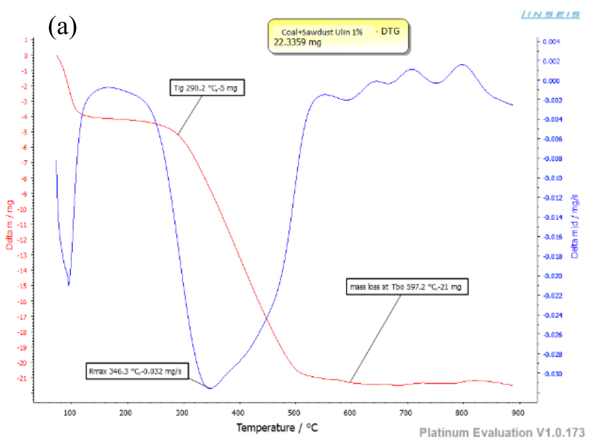
Table 4. Resume testing data DTG-DSC coal + Ironwood.

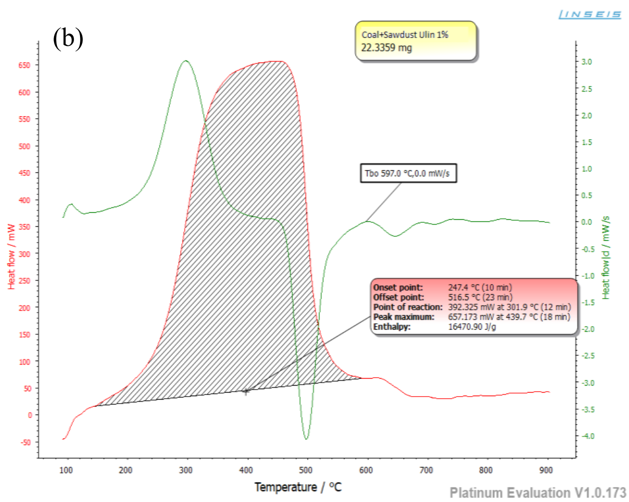
Sample	Weight (mg)	Mass Loss at Tig			Rmax mg/s
		Tig (°C)	Mg	%	
Coal + Sawdust Ironwood 1%	22,33590	290,2	5,0	22,4	0,032
Coal + Sawdust Ironwood 3%	9,76563	314,2	2,1	21,5	0,020
Coal + Sawdust Ironwood 5%	16,82790	307,0	1,6	9,5	0,030

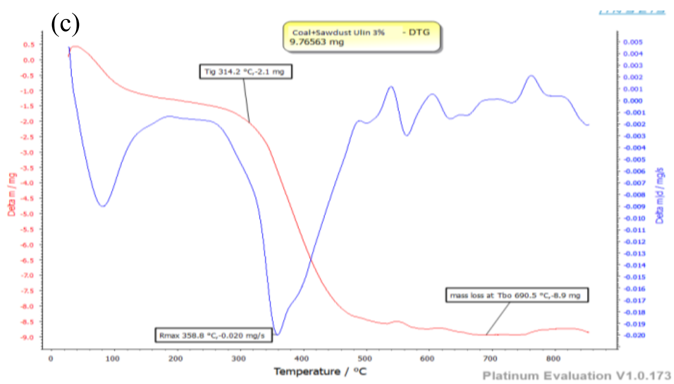
Sample	Tbo (°C)	Mass Loss at Tbo		Onset Point	
		mg	%	(°C)	Time (min)
Coal + Sawdust Ironwood 1%	597,2	21,0	94,0	247,4	10
Coal + Sawdust Ironwood 3%	690,5	8,9	91,1	315,2	14
Coal + Sawdust Ironwood 5%	688,2	14,0	83,2	249,1	17

Sample	Offset Point		Point of Reaction		T max (°C)	Enthalpy (J/g)
	(°C)	Time (min)	(°C)	Time (min)		
Coal + Sawdust Ironwood 1%	516,5	23	301,9	12	439,7	16.470,9
Coal + Sawdust Ironwood 3%	494	23	347,1	15	373,3	20.452,04
Coal + Sawdust Ironwood 5%	513,1	19	306,5	9	440,1	20.076,29

The DTG-DSC curve of the coal and ironwood mixture shows that the coal + 1% ironwood mixture starts burning faster, with the lowest ignition temperature (Tig) at 290.2°C and a mass loss of 22.4%. The coal + 1% ironwood mixture also exhibits easier ignition, with the highest Rmax value of 0.032 mg/s and a Tmax of 439.7°C. Consistent with coal combustion characteristics, a higher Tmax value indicates a greater propensity to ignite. This suggests that the coal + 1% ironwood mixture has a 1% higher ignition propensity compared to the other two mixture







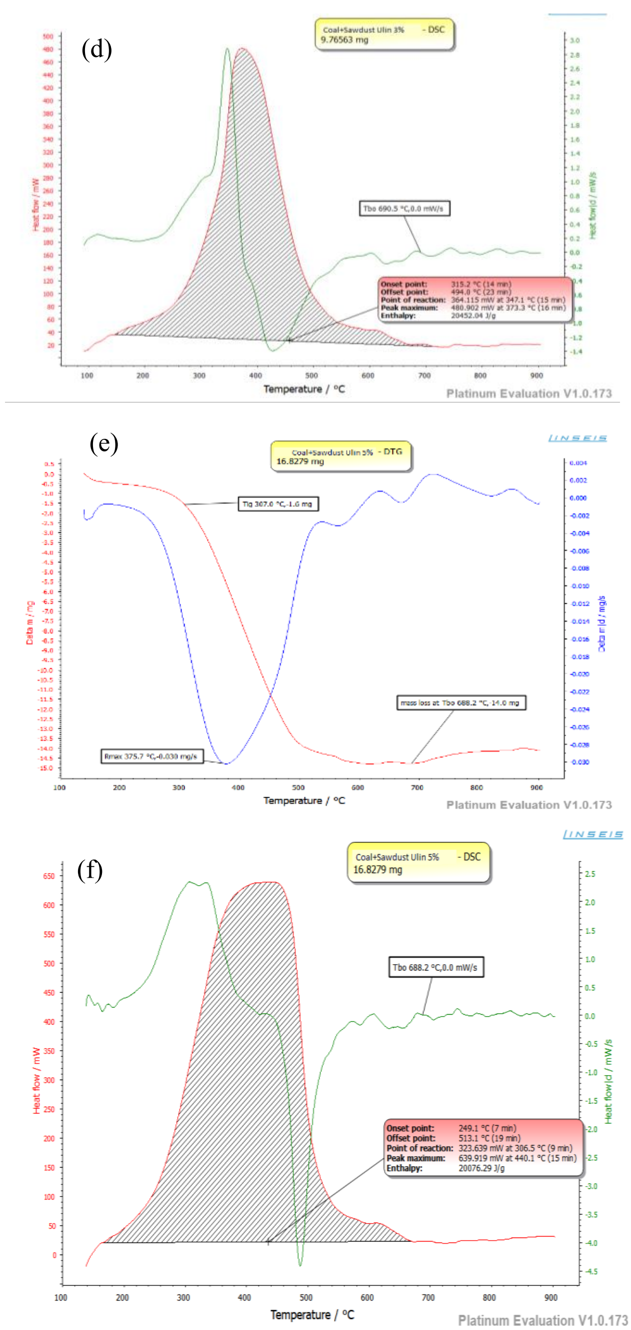


Fig. 14: (a) Curve DTG coal + ironwood 1% **(b)** curve DSC coal + ironwood 1% **(c)** curve DTG coal + ironwood **(d)** curve DSC coal + ironwood 3% **(e)** curve DTG coal + ironwood 5% **(f)** curve DSC coal + ironwood 5%.

Coal + 3% Ironwood has the lowest self-burning tendency with an enthalpy of 16470.9 J/g. The lowest ash content was obtained in a mixture of coal + ironwood 1% by 6%, where although the lowest Tbo is 597.2°C, the highest mass loss is 21% or 94.0%.

After looking at Fig. 8 to 14 related to DSC/TGA analysis of co-firing coal and 3 biomasses (rice husks, ironwood sawdust, and teak sawdust), there is no clear difference37,38). This is like the results of research by Hariana et al. (2020) which analyzed coal, sawdust, and co-firing coal + 10% sawdust with DSC / TGA analysis[39,40].

3.5 Challenges in Implementing Biomass Co-Firing in Coal Power Plants

Biomass co-firing in coal-fired power plants offers several environmental benefits, including reduced greenhouse gas emissions and increased utilization of renewable energy sources. However, to fully understand the potential of this technology, it is essential to consider the broader context of economic and operational challenges involved in implementing biomass co-firing on a large scale.

One of the major challenges in developing biomass co-firing is the higher cost of biomass compared to the rates offered by Indonesia's state-owned electric utility company[41]. This price disparity affects the continuity of biomass supply, particularly for wood biomass. Furthermore, the international wood pellet market adds competition for raw materials, exacerbating supply issues[42].

Improving the economics of co-firing involves accurately quantifying CO_2 reductions to enable monetization through carbon credit or other mechanisms. Additionally, establishing a stable supply chain for raw materials is challenging due to the limited number of biomass suppliers, making the program economically less viable compared to coal. Therefore, addressing these economic and supply chain challenges is crucial for the successful large-scale implementation of biomass co-firing in Indonesia.

Implementing biomass co-firing in Indonesia is a relatively new initiative, and it brings with it several potential operational challenges. For example, the use of biomass can lead to boiler tube fouling and corrosion, which can result in increased maintenance needs and efficiency issues[43,44]. To mitigate these challenges and improve the overall efficiency of biomass co-firing, it is essential to engage local communities in the biomass supply chain. This can be achieved through initiatives such as establishing biomass plantations or utilizing agricultural waste, which can also have the added benefit of boosting the local economy.

Standardizing biomass specifications is crucial for ensuring optimal performance of power plants. Consistent quality and characteristics of the biomass used will help in maintaining the efficiency and reliability of the combustion process. Introducing a 10% biomass co-firing rate can significantly contribute to achieving Indonesia's renewable energy targets and reducing greenhouse gas emissions[41,42].

However, to successfully implement this, robust government support is required in various areas, including technical regulations, technological advancements, reliable fuel supply, economic incentives, and comprehensive policy frameworks. Further, research and development efforts should focus on addressing the technical challenges associated with biomass co-firing, such as corrosion and fouling, and on optimizing combustion systems for different types of biomasses. Collaboration between government agencies, industry stakeholders, and research institutions will be key to overcoming these hurdles and realizing the full potential of biomass co-firing as a sustainable energy solution for Indonesia.

For effective co-firing, it is likely that the required biomass will need to be sourced from various regions. Therefore, there must be robust coordination in the collection and delivery of biomass to the coal-fired power plant sites. Ensuring cost-effectiveness and quality assurance in these operations is crucial for the success of biomass co-firing.

To achieve this, a well-organized supply chain must be established. This involves coordinating with local farmers, biomass suppliers, and transportation services to ensure a steady and reliable supply of biomass. Additionally, investments in infrastructure, such as storage facilities and processing plants, may be necessary to handle the biomass efficiently and maintain its quality during transportation and storage.

Quality assurance protocols must be implemented to ensure that the biomass meets the necessary specifications for efficient combustion. This includes regular testing of biomass for moisture content, calorific value, and other relevant properties. By maintaining high-quality standards, power plants can optimize combustion efficiency and minimize operational issues such as fouling and corrosion.

Moreover, economic considerations play a significant role in the viability of biomass co-firing. A detailed cost-benefit analysis should be conducted to compare the expenses involved in biomass procurement, transportation, and handling with the potential savings from reduced greenhouse gas emissions and improved energy efficiency. Financial incentives, such as subsidies or tax breaks, could be explored to make biomass co-firing more economically attractive for power plant operators.

In summary, the successful implementation of biomass co-firing requires comprehensive planning and coordination across the supply chain, stringent quality control measures, and thorough economic evaluation. By addressing these factors, biomass co-firing can become a viable and sustainable solution for reducing carbon emissions and enhancing the utilization of renewable energy sources in coal-fired power plants.

4. Conclusion

Based on the tests conducted, we can determine the characteristics of the fuels used in the co-firing of biomass and coal at the power plant. These fuels include coal, rice husks, ironwood sawdust, and teakwood sawdust, with biomass mixture compositions of 1%, 3%, and 5%. The conclusions drawn from these examinations are as follows:

a. The rice husk, ironwood sawdust, and teakwood sawdust biomass examined in this study exhibit lower calorific values compared to the tested coal. Specifically, their calorific values are 3,380 kcal/kg (adb), 4,465 kcal/kg (adb), and 4,460 kcal/kg (adb), respectively.
b. For every 1% addition of biomass, the theoretical combustion air requirements are reduced by 0.024 kg/kg fuel for rice husk, 0.003 kg/kg fuel for ironwood sawdust, and 0.009 kg/kg fuel for teak sawdust. If the volume of air supplied remains constant, this will result in excess air, which will reduce efficiency by 0.02% for rice husk and 0.01% for both ironwood and teak sawdust. However, these reductions in efficiency do not appear to be significant.
c. Each 1% addition of rice husk to coal reduces the fuel's calorific value by 19 kcal/kg. Similarly, adding sawdust reduces the calorific value by 7.5 kcal/kg for each 1% addition of ironwood sawdust and by 7.6 kcal/kg for each 1% addition of teak sawdust.
d. Coal reaches its ignition point at 443°C, while rice husk ignites at 312°C, ironwood sawdust at 324°C, and teak sawdust at 318°C. Adding biomass to coal lowers the fuel's ignition point, resulting in faster ignition and more rapid burning in the boiler combustion chamber.
e. Based on the analysis in the results and discussion sections, co-firing coal and biomass positively impacts to lowering the fuel's ignition point, resulting in faster ignition and burning in the boiler combustion chamber.

Further research is necessary to expand the scope of co-firing compositions, potentially increasing biomass content to 10%, 25%, and 50%. This will help confirm the availability of sufficient biomass supply for these levels and determine how many power stations can be supported. Additionally, studies using other types of biomasses are essential to identify various biomass sources with the potential to replace coal as fuel.

Acknowledgements

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