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Comparative Evaluation of the Influence of Organic Binders on the Physicochemical Characteristics of Coal–Biomass during Co-Firing

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Abstract

Coal–biomass co-firing is a practical approach to reducing the environmental impact of coal-based energy systems; however, differences in fuel properties often limit performance. This study investigates the role of organic binders, starch, molasses, and cellulose at varying amounts (5–25 g) in improving the physicochemical properties of coal–biomass blends. Key parameters evaluated include ignition temperature, ignition time, burnout rate, heat release rate (HRR), proximate and ultimate composition, and calorific value. Results show that binder type and proportion significantly influence combustion behavior. Cellulose exhibited superior performance, with optimal results at 15 g, achieving the lowest ignition temperature (326°C), shortest ignition time (12.0 s), highest burnout rate (0.541%/s), and peak HRR (34.0 kW), alongside improved calorific value (27.25 MJ/kg) and reduced nitrogen and sulfur contents. Starch showed moderate and stable performance at 15 g with ignition temperature (323.6 °C), ignition time (21.0 s), burnout rate (0.478%/s), HRR (21.2 kW), and calorific value (25.27 MJ/kg), while molasses performed least at the same binder proportions with ignition temperature (378 °C), ignition time (24.8 s), burnout rate (0.479%/s), HRR (17.4 kW), and calorific value (25.55), indicating that molasses has moisture retention and an increase in ash deposit propensity. Excess binder addition (>20 g) led to performance decline; thus, ≤20 g is recommended.

Keywords: binder; coal-biomass; co-firing; physicochemical; starch; molasses; cellulose

1. Introduction

Coal continues to play a dominant role in global electricity generation, particularly in developing and emerging economies where energy security and affordability remain critical concerns (Roni et al., 2017; IEA, 2022; Liang et al., 2024). However, coal combustion is a major contributor to greenhouse gas emissions, acid rain precursors, and particulate pollution, intensifying environmental and public health challenges (Crippa et al., 2019; Fakinle et al., 2020; Lv et al., 2022; Umubigho et al., 2025). As a result, significant research efforts have focused on transitional strategies that can reduce the environmental footprint of coal-based energy systems while maintaining the reliability of existing infrastructure. Biomass–coal co-firing has emerged as one of the most practical and immediately deployable approaches for achieving this transition (Roni et al., 2017; Liu et al., 2021; Guo et al., 2024).

Biomass is renewable, widely available, and carbon-neutral over its life cycle when sustainably sourced, making it an attractive supplement to coal in power generation systems (Fadele et al., 2021; Kivumbi et al., 2021; Sasangko et al., 2024).. Numerous empirical studies have demonstrated that blending biomass with coal can reduce net CO_2 emissions, lower sulfur content, and improve overall fuel sustainability (Mursito et al., 2020; Adeleke et al., 2022; Ashraf et al., 2022). However, biomass differs significantly from coal in terms of grindability, moisture content, volatile matter, ash composition, and combustion kinetics, which introduces technical challenges in co-firing applications (Wang et al., 2021; Yuan et al., 2021; Liu et al., 2023).Commercial co-firing systems are typically categorized into direct, indirect, and parallel configurations. Direct co-firing, the most widely adopted method, involves simultaneous combustion of coal and biomass in the same boiler and fuel preparation system (Liu et al., 2021). Empirical investigations by Wang et al. (2021) and Liu et al. (2023) show that direct co-firing is cost-effective but prone to operational problems such as slagging, fouling, corrosion, and limited biomass substitution ratios due to the lower ash melting temperature and fibrous nature of biomass. Indirect co-firing, which gasifies biomass to produce syngas prior to combustion, reduces ash-related problems and improves fuel flexibility, but increases capital and operational costs (Xu et al., 2020). Parallel co-firing allows higher biomass shares and reduces contamination risks by using separate boilers, yet it remains economically prohibitive for many installations (Roni et al., 2017; Liu et al., 2023). These constraints highlight the need for fuel-level optimization strategies that enhance combustion performance without requiring major infrastructure modifications.

One widely adopted fuel-level strategy is the densification of coal–biomass blends into briquettes or pellets using binders. Binders improve mechanical durability, handling, and storage, while also influencing combustion behaviour through changes in particle contact, porosity, volatile release, ignition characteristics and ash chemistry (Kaliyan & Morey, 2009; Hu et al., 2015; Obi et al., 2022; Umubigho et al., 2025). Proximate and ultimate analyses are commonly used to evaluate these changes, as they directly govern ignition temperature, ignition time, burnout rate, heat release rate, and emissions (Jahirul et al., 2012; Saikia & Baruah, 2013; Trubetskaya et al., 2019; Akimbomi et al., 2025;).

Empirical studies confirm that binder type plays a critical role in combustion performance (Hoang et al., 2021; Marangwanda et al., 2021; Nath et al., 2024). Hu et al. (2015) showed that biosolid binders enhance ignition and burnout compared to starch, while Saikia and Baruah (2013) reported that starch improves mechanical strength but has limited effect on ignition temperature. Increasing binder content improves cohesion but may reduce porosity and oxygen diffusion, thereby affecting burnout behaviour (Kaliyan & Morey, 2009; Jahirul et al., 2012).

Starch-based binders, widely used due to availability and biodegradability, provide stable ignition and moderate heat release (Borowski et al., 2017; Obi et al., 2022). However, higher dosages reduce pore connectivity and slow burnout (Aransiola et al., 2019; Lomunyak et al., 2024).Molasses, though capable of enhancing early ignition due to volatile sugars (Manyuchi et al., 2018; Dirbeba et al., 2021), tends to increase moisture and ash at higher proportions, leading to delayed ignition and reduced calorific value (Carnaje et al., 2018; Kebede et al., 2022; Tang et al., 2022; Unchaisri & Fukuda, 2022; Hariana et al., 2023).

Cellulose-based binders have gained attention for their fibrous structure and thermal stability, promoting improved ignition, oxygen retention, and sustained combustion (Altun et al., 2003; Wilaipon, 2009; Sakthivel et al., 2018; Galina et al., 2019; Olugbade et al., 2019). They also enhance burnout rate and heat release stability (Meena et al., 2024; Sweya et al., 2024). Advanced studies further show that cellulose improves heat release consistency, thermal efficiency, and combustion duration (Rantuch et al., 2021; Butler et al., 2023; Lubwama et al., 2024; Ayaa et al., 2025).

Beyond combustion, binders influence fuel properties. Starch and cellulose generally enhance fixed carbon and calorific value, while molasses increases volatile matter but may reduce heating value if moisture is not controlled (Borowski et al., 2017; Trubetskaya et al., 2019; Zhou et al., 2020; Dirbeba et al., 2021; Adeleke et al., 2022; Magida et al., 2022; Ni et al., 2022; Mekonen et al., 2024). Cellulose also improves carbon content and reduces oxygen fraction, enhancing energy density, while organic binders can reduce sulphur and nitrogen emissions (Mursito et al., 2020; Zhou et al., 2020; Magida et al., 2022; Guo et al., 2024; Lubwama et al., 2024; Ayaa et al., 2025).

Despite extensive research, most studies focus on single binders or limited conditions, with few integrating combustion characteristics and physicochemical analyses. This study addresses this gap by systematically evaluating starch, molasses, and cellulose binders at varying proportions (5–25 g) in coal–biomass co-firing. It examines their effects on ignition behaviour, burnout rate, heat release rate, and fuel properties to provide a comprehensive basis for optimizing binder selection for improved performance and reduced environmental impact.

2. Materials and Methods

2.1 Sample collection and Preparation

Bituminous coal (BC)was source from Nigeria Coal Corporation, Enugu, Nigeria. It was sun dried, pulverized and ground to powdery form to pass through sieve of 5 mm. 15 masses each weighing 65 g were prepared. It was then stored in an aerated polyethene bags till use to prevent caking. The sawdust (SD) was sourced from sawmill in Oleh, Delta State, Nigeria. It was cut, grind and sieve through 5 mm mesh. 15 masses each weighing 35g were prepared. The binders that were used in the production of the samples are; cassava starch (CS) were bought from Oleh market, Delta State. The starch obtained from the market was properly sun-dry and crush before passing it through a mesh size of 25 µm. Sugarcane molasses (SM) was also bought from BUA company in Port Harcourt. The cellulose (CL) used for the study was obtained from waste papers soured from various cyber cafe around Oleh. The pulp containing moisture is passed through a 25 µm mesh to obtain the cellulose which is then dried for 4 days. Five masses of 5g, 10g, 15g, 20g and 25g were weighed. Five masses of 5g, 10g, 15g, 20g and 25g of each of the binder was prepared. The binders were added to sun dried coal particles and sawdust and then evenly mixed. All samples were group into five for proper comparison. Group 1 consist of 5g samples, group 2 consist of 10g,, group 3, 4 and 5 consist of 15g, 20g and 25g respectively. Table 1. shows the various amount of binders in the mixtures.

Table 1: Pellets Coal-Sawdust-Binders Composition

Samples	Starch (g)	Molasses (g)	Cellulose (g)
1	5	5	5
2	10	10	10
3	15	15	15
4	20	20	20
5	25	25	25

2.2 Combustion Performance

Each m sample was placed on a heat-resistant surface, and a bunsen burner was used to apply flame to the edge of the briquette base. The time required for the briquette to visibly ignite was recorded using a stopwatch. Ignition time is calculated using Equation 1 (Kebede et al., 2022)

$$t_{ign} = t_1 - t_0 \quad (1)$$

where t_{ign} is the ignition time, t_1 is the time at which the sample ignites (sec), and t_0 is the time when the bursen burner is lit (sec)

The ignition temperature (T_{ign}) was determined by gradually heating each sample in a controlled environment until ignition occurred. A thermocouple (type K) was placed in close proximity to the point of flame initiation on the briquette surface. The Bunsen burner flame or an electric furnace was used to provide a uniform heat source. The temperature at which sustained ignition occurred was recorded as the ignition temperature. For accuracy, each sample was tested in triplicate, and the average ignition time and ignition temperature were reported.

To determine the burning rate, the sample was ignited at one edge using a Bunsen burner and once the sample was fully ignited and burning steadily, the Bunsen flame was removed to allow the sample to burn on its own. A stopwatch was used to record the total time taken for the sample to burn completely from ignition to the point where no further visible combustion occurred. After combustion, the residual unburnt material was weighed to determine the total mass of the burnt portion. The value of burning rate was obtained using Equation 2 (Kebede et al., 2022)

$$BR = \frac{m_0 - m_i}{t} \quad (2)$$

where BR is the burning rate (g/s), m_0 is the initial mass, and m_i is the residual mass after combustion.

The calorific value of the briquette samples was determined using a Parr 6200 Isoperibol Bomb Calorimeter equipped with bomb IDs 39905 and M39889, following standard calorimetric procedures. The calorific value represents the amount of heat released during the complete combustion of a fuel and is a key indicator of its energy potential.

Approximately 1 g of each briquette sample was ground to a uniform particle size and pelletized to ensure complete and consistent combustion. The pelletized sample was accurately weighed using an analytical balance and placed in a stainless steel sample holder (crucible). A measured length of nickel-chromium fuse wire was attached between the bomb electrodes and positioned in contact with the sample to facilitate ignition.

The crucible containing the sample was carefully placed inside the bomb calorimeter vessel. The bomb was then sealed tightly and filled with pure oxygen to a pressure of approximately 30 bar to ensure complete combustion. After oxygen charging, the bomb was immersed in a calorimeter bucket containing a known quantity of distilled water. The calorimeter assembly was placed in the calorimeter jacket, and the system was allowed to reach thermal equilibrium.

The sample was ignited electrically, and the temperature rise of the surrounding water was recorded automatically by the calorimeter system. The temperature increase resulting from combustion was used to calculate the gross calorific value (higher heating value, HHV) of the sample based on the calorimeter's energy equivalent and necessary corrections, including fuse wire and acid corrections.

The calorific value was calculated automatically by the Parr 6200 calorimeter software and expressed in calories per gram (cal/g). To ensure accuracy and reproducibility, each sample was tested in duplicate, and the average value was reported. The calorific value is converted to MJ/kg using Equation 3 according to NIST (2019)

$$CV(MJ/kg) = CV(cal/g) \times 0.0041868 \quad (3)$$

Heat Release Rate (HRR) is the amount of heat energy a material or fuel releases per unit time while it is burning. Calculated using Equation 4 (Martinka et al., 2023)

$$HRR = \frac{(m_1 - m_2)CV}{t} \quad (4)$$

where HRR = Heat Release Rate (kW), m_i = initial mass of sample (g), m_2 = final mass(ash)(g) , CV = calorific value (kJ/g) and t = burnout time

T_r = temperature rise

The thermal efficiency of each sample is obtain using Equation 5 (Getahun and Wagaw, 2024).

$$\eta = \frac{m_w C_p (T_b - T_0) + m_e L}{m_s CV} \quad (5)$$

Where; M_w = mass of water heated, C_w = specific heat capacity of water (4.184J/gk), T_b = final temperature, T_o=initial temperature of water, M_s = mass of sample burnt, CV = calorific value of fuel, m_e=mass of evaporated water and L=latent heat of evaporation. In bomb calorimeter, there is no change of phase and L is assumed zero (Parr Instrument Company, 2024).

2.3 Ultimate Analysis (Elemental Composition)

The elemental composition of the coal-PKS blends, including organic carbon (C), hydrogen (H), nitrogen (N), and sulfur (S), was determined using a CHNS elemental analyzer (PerkinElmer 2400 Series, USA) in accordance with ASTM D5373-16. Approximately 1g of each dried and homogenized sample was accurately weighed using a microbalance and loaded into a tin capsule provided by the analyzer. The tin capsule containing the sample was automatically introduced into a combustion furnace maintained at 950–1000°C. In the furnace, the sample underwent complete combustion in an oxygen-rich environment, producing CO_2, H_2O, N_2, and SO_2 gases.

These combustion gases were separated using a gas chromatograph (GC) column and detected via thermal conductivity detectors (TCD) to quantify the individual elements. The analyzer measured the percentage of C, H, N and S on an air dried basis based on the amount of each gas detected relative to the total sample mass. This was based on ISO 12902-CHN instrumental method.

The percentage of oxygen was calculated using Equation 6 (Afu et al., 2025)

$$O(\%) = 100 - (C + H + N + Ash + moisture) \quad (6)$$

2.4 Proximate Analysis

The proximate analysis evaluates the chemical properties of the blended samples. It was conducted to determine the moisture content, volatile matter, ash content and fixed carbon content.

Moisture Content: The moisture content of the samples was determined using the standard procedure specified in ASTM D2444-16. 5g of each blended sample was accurately weighed and placed in a clean wash glass. The samples were then transferred to a laboratory oven dryer and heated at a temperature of 105 ± 3 °C for 24 hours to remove all inherent moisture and until a constant weight is achieved. After drying, the samples were removed from the oven, cooled in a desiccator to prevent moisture absorption from the atmosphere, and weighed again. Moisture content is obtained using Equation 7 (Kebede et al., 2022).

$$MC(\%) = \frac{(W_i - W_f) \times 100}{W_i} \quad (7)$$

where MC is moisture content, W_i is initial mass of sample before drying and W_f is final mass of sample after drying.

Volatile Matter Determination (db %): The volatile matter (VM) content of the samples was determined in accordance with ASTM D3175-18. Approximately 1g of the oven-dried sample was placed in a covered crucible and introduced into a preheated Carbolite Gero ashing furnace (AAF 11/3 model, 30–3000 °C). The sample was heated at a temperature of 925 ± 20 °C for 7 minutes under controlled conditions to ensure the release of volatile components without complete combustion.

After heating, the crucible was removed from the furnace, cooled in a desiccator to avoid moisture absorption, and then weighed. The loss in mass, excluding moisture, was attributed to volatile matter. Results were reported on a dry basis (db %).

Volatile matter is calculated using Equation 8 (Kebede et al., 2022)

$$VM(db\%) = \frac{W_v}{W_d} \quad (8)$$

where VM is the volatile matter, W_d is the mass of the dried sample before heating (g), and W_v is the weight of the sample after volatile matter determination (g)

Ash Content Determination (db %): The ash content of the samples was determined in accordance with ASTM D3174-12. The residual samples obtained after volatile matter determination were used for ash analysis. These samples were placed in a Carbolite Gero muffle furnace (AAF 11/3 model, 30–3000 °C) and heated gradually to a temperature of 700 ± 50 °C to ensure complete combustion of all combustible material.

The samples were maintained at this temperature until only inorganic residue remained. After heating, the crucibles were removed from the furnace, cooled in a desiccator to prevent moisture absorption, and then weighed to obtain the final ash weight. The ash content, reported on a dry basis (db %) and calculated using Equation 9 (Kebede et al., 2022)

$$Ash\ (db\%) = \frac{W_2}{W_1} \quad (9)$$

where W_1 is the mass of sample before ash (g), and W_2 is the mass of residual ash after heating (g)

Fixed Carbon Content: The fixed carbon (FC) content of the samples was determined by calculation, using the difference method. Fixed carbon represents the solid combustible residue remaining after the removal of moisture and volatile matter, excluding ash. It was calculated by subtracting the sum of moisture content (MC), volatile matter (VM), and ash content (AC) from 100%.

The fixed carbon percentage on a dry basis (db %) and was calculated using Equation 10 according to Kebede et al. (2022)

$$FC(db\%) = 100 - (MC + VC + AC) \quad (10)$$

where:

MC = Moisture content (%); VM = Volatile matter (%); AC = Ash content (%)

3. Results and Discussion

3.1 Ignition Temperature

From Figure 1, cellulose samples show the lowest ignition temperatures, decreasing further with increasing binder proportion (e.g., 326 °C at 15 g). This supported Ayaa et al. (2025) and Lubwama et al. (2024) that indicated cellulose-rich binders stabilize combustion but may slightly raise decomposition temperature. Cellulose can produce lower ignition temperatures at well-dried states due to increased volatile release.

Binder type strongly influences ignition temperature. Among the three, Cellulose at 15 g is optimal for enhancing ignition, flame stability, and heat release. It is the most promising binder for improving ignition characteristics in coal–biomass blends. This indicates that the right proportion of cellulose optimizes ignition without oversaturating the blend. Starch provides consistency but not major benefits. Molasses, despite being a natural binder, hinders ignition and is less desirable unless used in very small proportions. Too much molasses adds excessive moisture and delays ignition. The findings disagree with Dirbeba et al. (2021) and Manyuchi et al. (2018) whose findings shows that molasses at moderate dosage reduce ignition temperature. The reason were assets by Aransiola et al., (2019) and Kebede et al., (2022) that excess molasses increases moisture and reduces oxygen diffusion needed for ignition. This results to higher temperature before ignition.

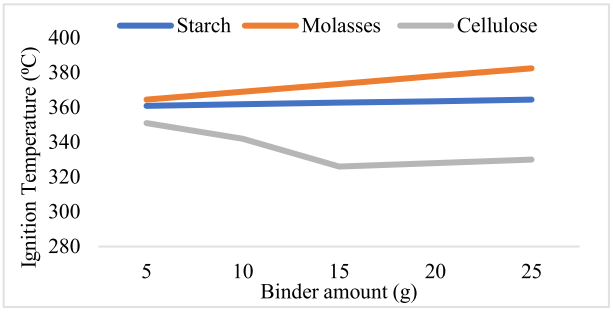

Figure 1: Ignition Temperature of Different Binders

3.2 Ignition Time

The results of the proximate and ultimate analysis of pig dung, cattle dung, 3.2 Ignition Time

From Figure 2, the ignition time for cellulose is lowest at any given amount. This suggests cellulose promotes easier ignition as cellulose tends to reduces ignition delay and promotes volatile release (hence lower ignition time). Optimal at 15 g where cellulose ignites in 12.0s about 40–60% faster than starch and about 55–58% faster than molasses at comparable amount of binder. Starch shows a gradual worsening with increase in binder amount (19.8s at 5g to 22.6s at 25g). It's relatively inert; useful when you need predictable ignition but not performance gains. The findings is in line with Obi et al. (2022) and Lomunyak et al. (2024), where starch improves particle contact, producing moderate ignition times. Molasses consistently delays ignition; its high moisture and sugary matrix require extra energy to dry/pyrolyze before ignition, producing the longest ignition times (up to 28.6 s at 25 g). The findings deviated from those of Manyuchi et al. (2018) and Dirbeba et al. (2021) when they reported that molasses-bound briquettes ignite faster due to easily released volatiles. The results however support that higher molasses proportion may reduce porosity and limit oxygen access, delaying ignition as asserted by Aransiola et al., (2019) and Kebede et al., (2022).

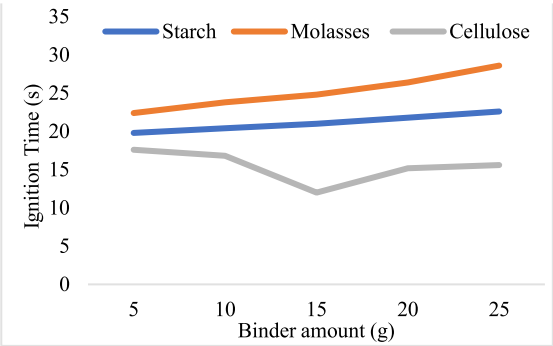

Figure 2: Ignition Time of Different Binders

3.3 Burnout Rate

From Figure 3, cellulose shows the highest burnout rate, indicating faster or more complete combustion. Cellulose increases the combustible fraction's reactivity (higher VM + stable FC) and promotes faster char oxidation — S9's 0.541 %/s is noticeably higher than starch or molasses at any given amount of binder. The results have a matched finding with Butler et al. (2023) and Trubetskaya et al. (2019), where cellulose-rich binders increase char combustion and sustain HRR. Molasses reduces burnout rate with increasing binder amount (moisture and non-combustible residue dilute reactive mass). At 25 g it's the slowest (0.439 %/s). The decreasing burnout of molasses at higher binder amount deviates from studies like Dirbeba et al. (2021), which reported enhanced early combustion. This according to Tang et al. (2022) and Nath et al. (2024) is that molasses densifies briquettes, restricting oxygen flow, slowing full burnout. Starch shows small fluctuations, but generally a modest decline in burnout with more binder supporting Aransiola et al. (2019) and Obi et al. (2022) that observed moderate burnout with good mechanical cohesion for starch binder. Cellulose not only enables early ignition but also ensures fuel is consumed more quickly and completely which is desirable for efficient combustion and lower unburned carbon losses.

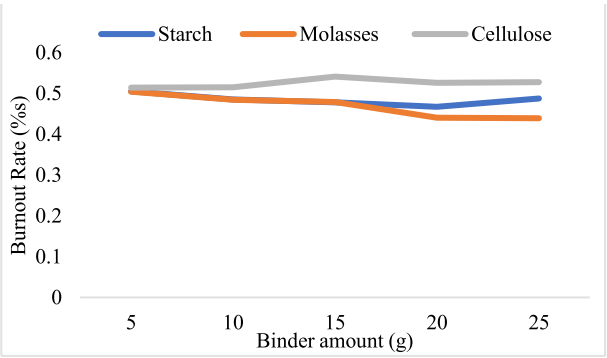

Figure 3: Burnout Rate of Different Binders

3.4 Heat Release Rate

Figure 4 showed that cellulose produces larger, sharper HRR peaks especially at 15 g (34.0 Kw), indicating rapid volatile release and energetic combustion. This contributes to higher thermal efficiency and stronger power pulses. This behaviour of cellulose binder as founded by this study matches Rantuch et al. (2021) and Lomunyak et al. (2024), where cellulose stabilizes combustion and sustains HRR. High HRR could also be due to more volatile release from cellulose decomposition in your conditions. Molasses lowers HRR consistently; the energy release is weaker and more drawn-out aligning with its higher moisture and ash. Dirbeba et al. (2021), reported higher early HRR. The lower HRR of this study may be due to dense coal-biomass, reducing oxygen diffusion and limiting combustion intensity. Starch remains middling and relatively flat across doses supporting Liu et al. (2021) and Obi et al (2022). This moderate HRR is due to good particle contact and moderate porosity of starch.

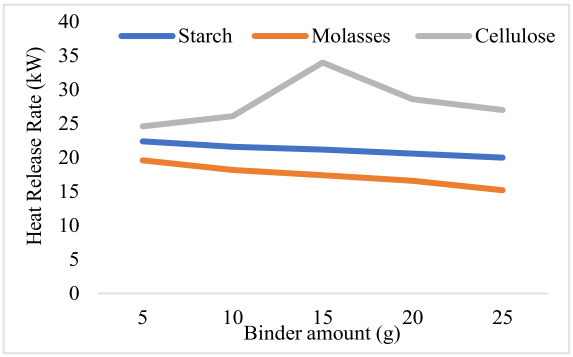

Figure 4: Heat Release Rate of Different Binders

3.5 Analysis of Carbon Content

From Figure 5, cellulose binder showed the highest percentage of carbon at each binder amount. It recorded the highest carbon content at 5g (63.9 %), indicating superior thermal energy potential. The increase in carbon from 57.8 % to 63.9 % across samples aligns with findings by Adeleke et al. (2022) and Kanwal et al. (2022), who observed enhanced carbon concentration and improved energy density when optimal binder ratios were used. The deviation observed at higher binder loadings (25 g) where carbon decreases slightly may be attributed to binder saturation, causing incomplete compaction and higher oxygen retention which support Marangwanda et al., (2021).

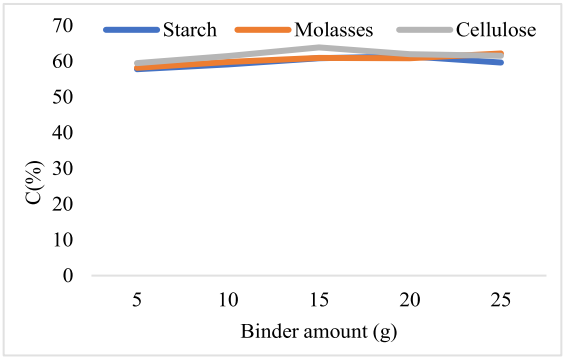

Figure 5: Analysis of Carbon Contents of Different Binders

3.6 Analysis of Hydrogen Content

Figure 6 showed that hydrogen contributes to combustion efficiency and flame propagation. Cellulose also have the highest percentage of hydrogen at various amount of the binder peaking to 5.8% at 15g. The Figure also showed a moderate rise in H (4.8 % to 5.8 %) at optimal cellulose binder amount suggesting an improved volatile composition which aid ignition, consistent with Ni et al. (2022) who reported enhanced volatiles and flame temperature when increasing rice husk ratio in coal blends. Starch and molasses showed less improvement, reflecting their relatively lower hydrogen enrichment and higher water retention, supporting Adeleke et al. (2022)'s observation that inorganic or sugar-based binders slightly suppress hydrogen content due to binding chemistry.

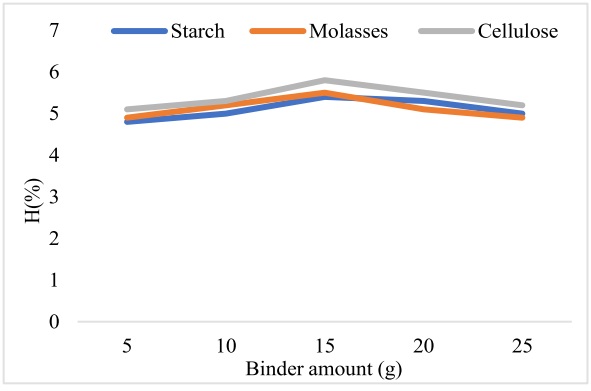

Figure 6: Analysis of Hydrogen Content of Different Binders

3.7 Analysis of Nitrogen Content

From Figure 7, the multiple bar chart showed that Nitrogen influences NO_x emissions. Lower nitrogen implies cleaner combustion. From the bar chart below, cellulose at 15 g (1.70 %) exhibited the lowest nitrogen, showing potential for reduced NO_x emissions, agreeing with Zhou et al. (2020) and Liu et al. (2021), who both demonstrated that optimized biomass ratios reduce NO_x formation through volatile-phase reactions and fuel staging. Samples with higher amount of binder (20–25 g) showed increased N content again, likely due to incomplete de-volatilization or nitrogen-rich intermediates. This support the findings of Magida et al. (2022) on microalgae–coal blends where excess binder nitrogen increased NOx output.

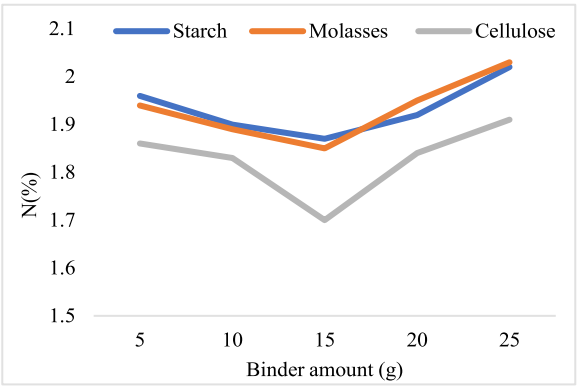

Figure 7: Analysis of Nitrogen Content of Different Binders

3.8 Analysis of Sulphur Content

From Figure 8, all binders significantly reduced Sulphur from 0.82 % to 0.62 % with the minimum value occurring under cellulose binder at 15g. It is known that Sulphur contributes to SO_2 emissions, thus lower values are desirable which is in line with Ashraf et al. (2022) and Kanwal et al. (2022) who observed 15–25 % reductions in SO_2 emissions with increasing biomass proportion. Cellulose performed best, showing the binder's sulphur-free and cellulose-rich nature to mitigates sulphur carryover. Slight Sulphur rebound at high doses (>20 g) could indicate organic sulphur reformation during curing: a similar to deviations noted by Lv et al. (2022) during co-firing with straw.

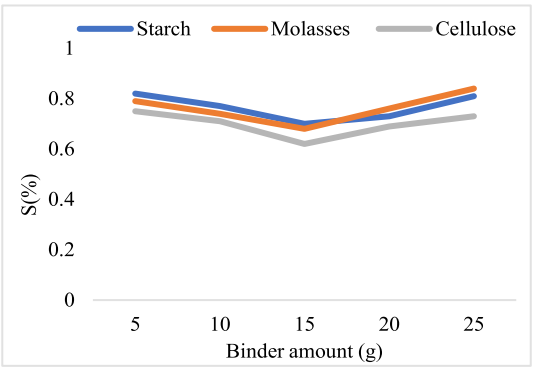

Figure 8: Analysis of Sulphur Content of Different Binders

3.9 Analysis of Oxygen Content

From Figure 9, Oxygen decreased across all binders up to 20g. Oxygen decreased notably with cellulose 15 g (27.9 %), correlating with improved carbonization and combustion stability. Oxygen content determines combustion reactivity and influences volatility. Similar oxygen reduction trends have been observed by Sakthivel et al. (2018) and Galina et al. (2019), who attributed such results to improved binder–fuel integration and reduction of oxidizing surface groups during torrefaction. The slight increase at higher doses (>20 g) may be due to excess binder moisture, decreasing densification and increasing oxygen retention.

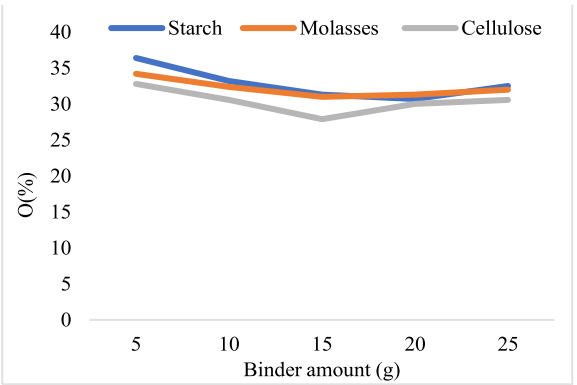

Figure 9: Analysis of Oxygen Content of Different Binders

3.10 Moisture Content

From Figure 10, Starch-bound samples showed MC values between 3.00%–3.50%, with a slight rise at 25 g (3.40%), suggesting mild moisture retention due to starch's gelatinous nature. Molasses-bound samples exhibited the highest MC values (3.20%–3.60%), especially at 25 g, because molasses is highly viscous and hygroscopic, which can trap water during curing. Cellulose-bound samples had the lowest MC (2.80%–3.20%), with the minimum (2.80%) occurring at 15 g, indicating excellent dryness and compaction efficiency. The low moisture in cellulose coal-biomass promotes faster ignition and better heat transfer.

This observation aligns with Magida et al. (2022) and Kanwal et al. (2022), who found that fibrous binders (like cellulose) reduce moisture retention and improve thermal stability. The slightly higher MC in starch and molasses briquettes agrees with Hu et al. (2015) and Adeleke et al. (2022), who reported that carbohydrate-based binders tend to retain moisture due to hydrogen bonding with water molecules. Also, reviews and experimental work from Aransiola et al., (2019) and Dirbeba et al., (2021) emphasize that incomplete drying or wet binders increase MC and reduce calorific value.

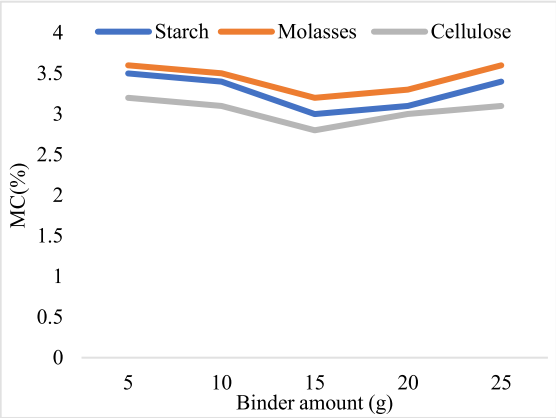

Figure 10: Moisture content of Different Binders

3.11 Volatile Matter

From Figure 11, Volatile matter content ranged between 45.50% and 62.50%, showing variations among binder types and amount. Starch samples exhibited VM values between 46.00% and 49.50%, generally decreasing with binder amount, implying more stable carbonization at higher binder proportions. Molasses samples ranged from 45.50% to 48.80%, showing a similar downward pattern, possibly due to higher binder loading suppressing volatile release during pyrolysis. Cellulose samples however, recorded significantly higher volatile contents (47.00%–62.50%), peaking at 62.50% at 15 g, indicating enhanced de-volatilization and better flammability. High VM enhances ignition and flame propagation due to the release of combustible gases (CO, CH_4, H_2). The cellulose results support Sakthive et al. (2018) and Marangwanda et al. (2021), who noted that cellulose-rich materials promote higher volatile yields and faster ignition. The trend deviates slightly from Altun et al. (2003), who observed a steady decline in volatile matter at higher binder loads; this difference could be due to the higher drying temperature and cellulose fiber porosity used in this study. Many TGA and cone-calorimeter studies (e.g., Galina et al., 2019; Marangwanda et al., 2021; Tang et al., 2022; Ni et al., 2022) show that higher VM leads to larger early HRR and shorter ignition time, consistent with the high calorific value and heat release rate just as seen in cellulose.

Figure 11: Volatile Matter of Different Binders

3.12 Ash Content

From Figure12, the ash content ranged from 1.20% to 8.00%, showing clear binder-related differences. Starch samples recorded moderate ash values between 6.00%–7.00%, consistent across binder amount, suggesting stable inorganic residue formation. Molasses samples exhibited the highest ash contents (6.50%–8.00%), with a steady increase as the amount of binder increased. This is attributed to the inherent mineral salts and impurities in molasses, which form non-combustible residues upon firing. Cellulose samples had the lowest ash content (1.20%–5.00%), with the minimum (1.20%) at 15 g, confirming cleaner combustion. Lower ash content improves combustion efficiency and minimizes slagging and fouling tendencies. These results support Lv et al. (2022), Adeleke et al. (2022) and Hariana et al. (2023), who found that increased biomass proportion or fibrous binders reduce ash accumulation. Unchaisri & Fukuda, (2022) also reported same finding that low ash reduces deposition and slagging risk adding that molasses can introduce minerals that raise ash. Molasses is also often volatile-rich but can contain more non-combustible minerals resulting to higher ash. However, the high ash content in molasses-bound samples deviates from Ni et al. (2022), who reported reduced ash at optimal molasses levels. This is likely because the molasses used in this experiment contained higher mineral impurities.

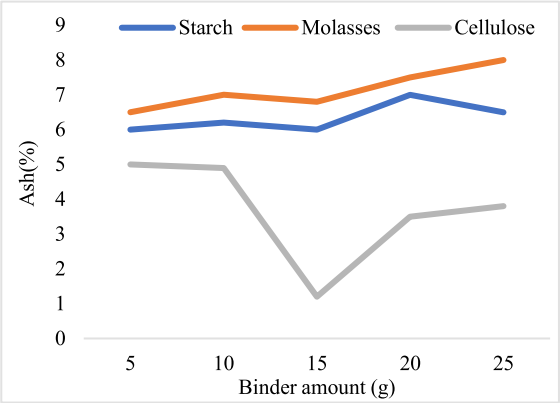

Figure 12: Ash Content of Different Binders

3.13 Fixed Carbon

From Figure 13, fixed carbon ranged from 33.50% to 46.10%, indicating strong potential for sustained combustion. Starch-based samples showed FC values between 41.00% and 44.00%, increasing with amount of binder due to improved carbon retention. Molasses samples ranged from 41.10% to 43.70%, showing minor variation, though slightly lower than starch. This could be due to early combustion of sugars during firing, leaving less residual carbon. Cellulose samples displayed FC values between 33.50% and 46.10%, with the highest FC (46.10%) at 25 g, showing the material's strong carbon structure. However, the lowest FC (33.50%) at 15 g corresponded to the high volatile matter at that binder amount, showing a trade-off between easy ignition and sustained burn. This relationship between FC and VM is consistent with Adeleke et al. (2022) and Hu et al. (2015), who reported that as volatile matter increases, fixed carbon tends to decrease due to faster de-volatilization during combustion. The findings also support prior empirical reviews of Manyuchi et al. (2018); Aransiola et al. (2019); Trubetskaya et al., (2019); Dirbeba et al., (2021 and Obi et al., (2022) report that cellulose binders can either increase FC (after carbonization) or produce higher VM depending on processing/curing noting that optimal binder dosing is necessary: small amounts improve FC and density; Too much amount of binder can increase VM or moisture depending on binder chemistry.

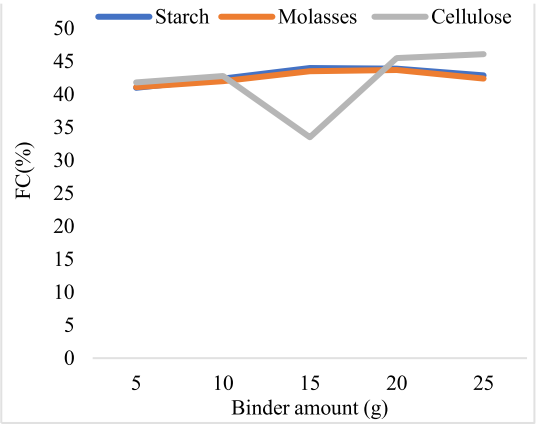

Figure 13: Fixed Carbon of Different Binders

Table 2: Calorific value of Coal-Biomass Co-firing using different Binder type and proportion

Samples	Binders CV (MJ/kg).		
	Starch	Molasses	Cellulose
1	23.12	23.44	24.30
2	23.98	24.58	25.47
3	25.27	25.55	27.25
4	25.42	24.91	25.98
5	24.25	24.32	25.36

The calorific value results demonstrate that binder proportion significantly influences the heating potential of coal–biomass blends. For starch-bound blends, CV increased from 23.12 MJ/kg at 5g (5%) to a maximum of 25.42 MJ/kg at 20g (17%), before declining slightly to 24.25 MJ/kg at 25g (20%). The progressive improvement up to 17% inclusion agrees with Hu et al. (2015), who observed that binder proportions around 10–20% improved energy density and heating value due to improved inter-particle bonding before reaching a saturation point. Similarly, Aransiola et al. (2019) reported improved calorific values at starch inclusion levels between 10–15%, attributing this to improved particle bonding and enhanced carbon retention. Adeleke et al. (2022) also observed improved energy density at moderate binder ratios due to enhanced structural integrity of pellets. The slight decline at 20% starch aligns with Lomunyak et al. (2024), who found that excessive starch loading reduces pore connectivity and oxygen diffusion, thereby moderating combustion efficiency and net heating value. This suggests that starch performs optimally at moderate inclusion (≈13–17%) but begins to dilute combustible carbon at higher proportions.

Molasses-bound samples exhibited CV increasing from 23.44 MJ/kg at 5g (5%) to a peak of 25.55 MJ/kg at 15g (13%), then decreasing at 20-25g (17–20%) inclusion. The peak at approximately 13% binder supports Manyuchi et al. (2018) and Dirbeba et al. (2021), who reported enhanced energy output at moderate molasses levels of 10-15% due to the presence of combustible sugar components contributing to volatile combustion. They report that beyond 15% calorific value is significantly lower because of increased volatile components and reduced fixed carbon contribution. The decline beyond 13% is consistent with Carnaje et al. (2018) and Kebede et al. (2022), who observed that higher molasses proportions above 15% increase moisture retention and ash formation, lowering effective calorific value. Tang et al. (2022) further explained that excessive molasses densifies pellets and restricts oxygen diffusion, which can reduce combustion intensity and heating efficiency.

Cellulose-bound blends recorded the highest CV overall, increasing from 24.30 MJ/kg (5%) to a maximum of 27.25 MJ/kg (13%), followed by a moderate decline at 17–20%. The strong improvement up to 13% inclusion agrees with Lubwama et al. (2024) and Ayaa et al. (2025), who demonstrated that cellulose binders increase carbon concentration and reduce oxygen fraction, thereby improving higher heating value. This trend is further supported by Borowski et al. (2017) and Trubetskaya et al. (2019), who reported that fibrous organic binders preserve fixed carbon and enhance energy density when applied at optimized levels of 10-15%. The slight reduction beyond 13% corresponds with the densification behaviour described by Kaliyan and Morey (2009), where excessive binder addition reduces porosity and limits efficient combustion.

4. Conclusion

This study examined the influence of binder type (starch, molasses, and cellulose) and proportion (5–25 g) on the physicochemical and combustion performance of coal–biomass blends. Results show that binder chemistry and proportion significantly affect ignition behaviour, combustion performance and fuel properties. All binders demonstrated the best performance at 15 g, with cellulose having the lowest ignition temperature, shortest ignition time, highest burnout rate, and peak heat release rate. It also produced the highest calorific value and reduced nitrogen and sulphur contents, indicating improved environmental performance. Starch showed moderate and stable behaviour, while molasses reduced combustion performance at higher proportions due to increased moisture and ash. Excess binder addition (>20 g) led to performance decline across all binders. Overall, organic binder at 15g (13%) is recommended as the optimal binder for enhancing combustion performance and fuel quality in coal–biomass co-firing systems.

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