



EVALUATION OF BINDER COMPATIBILITY IN OPTIMISED PALM KERNEL SHELL-COAL BLENDS FOR ASH REDUCTION AND ENERGY OPTIMISATION SUSTAINABILITY

¹Erokare, E. T., ²Ekpu, M., ²Sinebe, J.E., ²Sada, S.O., ²Ikpeseni, S.C., ³Atsu, A.M.

¹Department of Agricultural and Biosystem Engineering, Southern Delta University, Ozoro

²Department of Mechanical Engineering, Delta State University, Abraka, Nigeria

³Mechanical Engineering Department, Tamale Technical University, Ghana

Corresponding Author's address: erokaretega.e@gmail.com

Abstract

This study investigated the effects of three locally sourced binders—cassava starch (CST), wastepaper (WP), and Styrofoam (SF)—on the synergistic combustion of palm kernel shell (PKS) and coal pellets for ash reduction and energy optimisation. Pellets were produced at two blend ratios (10% PKS:90% coal and 20% PKS:80% coal) with a constant binder composition of 30%. The samples were characterised using bomb calorimetry for calorific value, proximate analysis for moisture, volatile matter, ash, and fixed carbon content, and X-ray fluorescence for ultimate analysis (carbon, hydrogen, nitrogen, sulphur, and oxygen). The control samples (binderless) exhibited the highest calorific values (19.98–21.06 MJ/kg), while binder-enhanced pellets showed lower values (12.07–18.11 MJ/kg). Proximate analysis revealed that binder addition significantly reduced ash content, with cassava starch achieving the greatest reduction of 46% (from 19.72% to 10.59%) in 20% PKS blends, and wastepaper demonstrating the lowest ash content (11.95%) in 10% PKS blends. Ultimate analysis showed that the addition of wastepaper elevated the carbon content to 70.28% in 20% PKS blends, while cassava starch optimised the balance between fixed carbon (43.70%) and volatile matter (43.96%). Sulphur content increased with binder addition, particularly with wastepaper (1.00%), highlighting trade-offs in emissions. The 20% PKS blend with a cassava starch binder emerged as the optimal formulation, achieving substantial ash reduction, an acceptable calorific value (17.00 MJ/kg), and promising emission-reduction potential. This research demonstrates that binder selection critically influences fuel properties and provides validation parameters for developing sustainable binder-enhanced PKS-coal pellets as a cleaner energy alternative for co-firing applications.

Keywords: Agricultural waste, Ash reduction, Binder optimization, Cleaner energy, Palm kernel shell, Styrofoam

1. INTRODUCTION

The International Energy Agency (IEA, 2025) predicts rising energy demand if current economic and policy trends persist. Concurrently, concerns about global warming stemming from the greenhouse gas effects of fossil-fuel CO₂ emissions have spurred the quest for carbon-neutral energy sources (Sinebe et al., 2026). The existing energy framework especially in developing nations is predominantly dependent on fossil fuels, leaving a significant gap between anticipated emissions and the required reductions to limit global warming to 1.5°C (United Nations Environment Programme, 2024).

Simultaneously, developing countries must expand access to affordable electricity while transitioning to low-carbon systems, underscoring the complexity of achieving both justice and sustainability in energy policy (World Bank, 2024). The International Renewable Energy Agency (IRENA, 2024) stated that renewable energy is a crucial option, requiring a threefold increase in deployment by 2030 to meet demand growth and achieve emission-reduction objectives. Coal is a fundamental energy resource globally, particularly in poor countries. Nevertheless, its combustion remains a significant source of greenhouse gas and

pollutant emissions. Onochie *et al.* (2017) reported that a feasible transitional approach to mitigate this impact is co-firing coal with biomass, notably palm kernel shell (PKS). This pattern can mitigate the environmental impact of existing power infrastructure while improving energy security and efficiently using agricultural waste. Studies highlights the potential of biomass to mitigate carbon emissions in tropical regions dependent on coal (Kuswa *et al.*, 2025; Erokare *et al.*, 2026). Furthermore, Onochie *et al.* (2024) provide evidence that co-firing palm kernel shell (PKS) with coal directly reduces emissions of CO₂ and SO₂. This substitution can be effectively implemented at scale; performance evaluations suggest that partial replacement of 5–20% of coal with PKS can lower greenhouse gas emissions without compromising boiler efficiency (Nainggolan *et al.*, 2023).

Pelletization enhances the management, storage, and efficient burning of biomass-coal composites. Binder addition improves durability and consistency; nevertheless, its effects go beyond simple particle agglomeration (Erokare *et al.*, 2026). Studies suggests that binders may affect critical fuel properties (Orhorhoro *et al.*, 2023; Kolo *et al.*, 2024; Anguruwa *et al.*, 2024), Erokare *et al.*, 2025; Sinebe *et al.*, 2026) such as ash content, calorific value, and emission profiles; however, the effects on palm kernel shell (PKS) when combined with coal are not well understood. Onochie *et al.* (2025) found that the emissions of CO₂ and SO₂ from pelletized mixtures of palm kernel shell (PKS) and coconut shells are affected by the mixing ratio. Conversely, Chen *et al.* (2015), Pradhan *et al.* (2018), and Peng *et al.* (2013) proved that torrefaction and co-pelletization improve fuel quality while

simultaneously introducing unpredictability in ash and energy content. Kuswa *et al.* (2025) examined ash-related challenges in PKS combustion and highlighted the impact of additives and binders on performance. Additionally, Onochie *et al.* (2024) assessed the compatibility of biomass–coal blends for cleaner energy applications and sustainable development, emphasizing the need for thorough evaluations of pelletization methods. These findings collectively demonstrate that understanding binder interactions is essential to ensuring that PKS–coal pelletization is a reliable technique for cleaner energy generation.

This study investigates the effects of three locally sourced binders, which include: cassava starch (CST), waste paper (WP), and Styrofoam (SF), on the synergistic combustion of palm kernel shell (PKS) and coal pellets, employing an optimized blend ratio of 10% to 90% and 20% to 80%. The aim is to clarify the intricate effects of these binders on the optimized mix with respect to proximate and ultimate properties, as well as fluctuations in calorific value. Moreover, identify the optimal binder for ash reduction and energy optimization in PKS-coal co-firing systems. The globe faces urgent demands to reduce carbon emissions and mitigate environmental impacts. To advance cleaner, sustainable energy, it is crucial to understand the effects of binder inclusion in biomass-coal co-firing. This study investigates the complexities of balancing PKS-coal with various binder additives and emphasises the consequent effects on combustion emissions, particularly regarding ash reduction and energy optimisation. Numerous studies have already investigated biomass co-firing, pellet

optimization, and emissions analysis. Nonetheless, no research has investigated the impact of binders on ash reduction and energy optimization of PKS-coal, using blended cassava starch, Styrofoam, and waste paper as binders to assess their effects. This study analyses the impact of various binder blends on PKS-coal, providing insights into sustainable energy production and enabling informed decisions that promote environmental stewardship and energy security. The study will elucidate the optimal fuel mixture for the PKS-coal/binder blend ratio, facilitating optimal ash reduction and energy efficiency, and examine its effects in the established power industry employing biomass-coal fuel.

2 MATERIALS AND METHODS

2.1 Data Collection and Preparation of Samples

Coal lumps and palm kernel shell, both pulverised, along with various binders in their solid and paste states. The coal lumps acquired from the Ogui coal dump site and palm kernel shells were procured from the oil palm mill in the Enugu North Local Government Area of Enugu State. The coal and palm kernel shell samples were sun-dried for one week to

Table 1: Components of Pellet Feedstock

Pellets Samples	Coal (% wet)	PKS (% wet)	Binder (30% wet)
Sample 1	90	10	None
Sample 2	90	10	CST
Sample 3	90	10	WP
Sample 4	90	10	SF
Sample 5	80	20	None
Sample 6	80	20	CST
Sample 7	80	20	WP
Sample 8	80	20	SF

PKS = Palm kernel Shell, CS = Coconut Shell, SD = Sawdust, CST = Cassava Starch, WP = Wastepaper, SF = Styrofoam.

2.3 Pelletization of PKS-coal samples

Figure 2 (A–H) illustrates pellets generated mechanically by a screw press. The pellets

diminish moisture content and facilitate pulverisation.

2.2 Preparation of pellet samples.

Studies conducted by various authors (Vamvuka *et al.*, 2003; Baxter, 2005; Fernando, 2012; Al-Qayim *et al.*, 2019; Wang *et al.*, 2020; Onochie *et al.*, 2022; Ighodaro & Ndem, 2023; Umubigho *et al.*, 2025) indicates that optimal mixing ratios for co-fired biomass-coal pellets applications are 10% and 20%. The specified ratios were employed to manufacture pellets, utilising 30% of the total sample weight for the binder mix, which aligns with the binder ratios used by Kolo *et al.* Kolo *et al.* (2024) and Anguruwa *et al.* (2024) to produce various briquetting samples intended for heating and power generation. The research utilised cassava starch, wastepaper, and Styrofoam as binding materials to make pellets, which were subsequently sun-dried for 1 week (Onochie *et al.*, 2017) to reduce moisture content and enhance hardness prior to characterisation. Figure 2 (A–H) illustrates the pellets generated from various samples, whereas Table 1 presents the percentage composition of each component in the pellet feedstock.

comprise a 10% PKS-Coal and 90% mix ratio with cassava starch (CST), Styrofoam (SF), and wastepaper (WP) for various samples.

Using a 20% PKS-Coal and 80% mix ratio with cassava starch (CST), Styrofoam (SF), and wastepaper (WP) for various samples. The pellets were manufactured using a manual screw press pelletisation apparatus. The pellets

were subsequently sun-dried for one week (Onochie *et al.*, 2017) to reduce moisture content and enhance hardness before laboratory characterisation. Figure 2 (A–E) shows the pellets generated from the various samples.



Fig 2 A–H Pellet samples produced from various PKS-coal-binder formulations

2.4 Calorific values of fuel sample (CV)

5g of the sample was weighed and carefully placed in a combustion crucible inside the bomb. The bomb was filled with oxygen at high pressure (Approximately 25 -30atm). The bomb was submerged in a mass of water and ignited by an electric spark. The initial and the final temperature of the water were recorded, and the temperature rise was generated automatically in MJ/Kg

$$CV = \frac{(W+w) \times \Delta T}{m} \dots \dots \dots (1)$$

W = water equivalent of the calorimeter (mass x specific heat of water)

w = Mass of water in the calorimeter

ΔT = rise in water temperature ($^{\circ}C$)

m = mass of fuel (g)

2.5 Proximate Analysis of Fuel Samples

For the proximate analysis, the Steriox model equipment was used. This entails the physical properties of the fuel pellets, including moisture, ash, volatile matter, and fixed carbon.

2.5.1 Volatile matter of fuel sample (VM): A

Clean, dry, and weighed empty crucible was noted as (W1). 1g of the powdered sample was

placed in a crucible and reported as (W2). This was covered with a lid and put in a preheated furnace at 950 °C for 10 minutes to achieve complete combustion. It was removed and cooled in a desiccator and weighed as (W3). The final results were obtained.

Calculation:

$$VM = \frac{(W2-W3)}{(W2-W1)} \times 100 \dots \dots \dots (2)$$

.. (2)

W1- weight of empty crucible

W2- weight of crucible+ dry sample

W3- weight of crucible+ residue after heating

2.5.2 Ash content of fuel sample (AS): A Clean, dry, and weighed empty crucible was noted as (W1). 1g of powdered sample was placed in a crucible (W2) and heated to 700 °C in a furnace for 1 hour to complete combustion, until a whitish appearance was observed. It was removed and cooled in a desiccator. The ash and the crucible were weighed and noted as (W3). The final results were obtained.

$$\text{Calculation: } AC = \frac{(W2-W3)}{(W2-W1)} \times 100 \dots \dots \dots (3)$$

2.5.3 Moisture content analysis (MC): The Gallenkamp model was used to determine the moisture content. A clean, dry, and weighed empty container was noted as (W1). 1g of the powdered sample was placed in a container and noted as (W2). This was placed in a hot-air oven at 105 °C for 1 hour until a constant weight was obtained for complete combustion. It was removed and cooled in a desiccator and weighed as (W3). The final results were obtained.

$$\text{Calculation: } MC = \frac{(W2-W3)}{(W2-W1)} \times 100 \dots \dots \dots (4)$$

W1- weight of empty container

W2- weight of container+ wet sample

W3- weight of container+ dry sample

2.5.4 Fixed carbon of fuel sample (FC): The fixed carbon was determined using the formula.

$$FC = 100 - (\%VM + \%AC + \%MC) \dots \dots \dots (5)$$

Where VM, AC, and MC are volatile matter, ash content, and moisture content, respectively.

2.6 Ultimate Analysis fuel samples

The ultimate analysis of the co-fired fuel sample pellets provides details on the elemental chemical composition of the samples. It provides a means to estimate fuel quality (Yaka et al., 2022). The percentage contents of constituents (carbon, hydrogen, nitrogen, and sulfur) were determined using an X-ray fluorescence (Xenometrix Genius-IF series). This analysis helps determine the amount of air required for complete combustion, the volume and composition of combustion gases, and the heat of combustion of pellets, which is primarily determined by their carbon and hydrogen content. The standard operating procedures are stated below:

- Prepare a sample cup with Prolene thin film. Ensure the thin film surface is smooth.
- Pour the pulverised sample (s) into a thin film-covered cup. Ensure the sample is filled to a third of the sample cup (approx. 10 –15g).
- Cover the lid of the sample cup. Ensure there are no leaks or loose particles on the thin film layer, and that the lids are tightly sealed.
- Insert the sample in the sample turret of the Genius-IF XRF. (If the sample is pelletized, ensure there are no cracks or loose particles on the surface.)
- Warm X-ray Lamp
- On the RUN tab, set voltage and emission current values to ensure that observed dead time is between 35-40kV; Stop Acquisition if observed dead time is below or above the required range.
- Run analysis to obtain the spectrum.

- Open XRS-FP Software
- Upload Master Oxide.tfr file
- Upload the obtained Spectra file of the sample
- Process > Process Spectrum
- Process > Analyse Spectrum
- Obtain results and print to a save file.

3. RESULTS AND DISCUSSION

3.1 Calorific Values of Co-fired Pellets (PKSC)

Table 2 and Fig. 3 illustrate the calorific values of co-fired palm kernel shell–coal (PKSC) pellets with varying biomass ratios and binder formulations. Control pellets, Sample 1 (10% PKS, 90% coal) and Sample 5 (20% PKS, 80% coal), both devoid of binder, had the most remarkable energy contents, ranging from 19.98 to 21.06 MJ/kg. These findings align with those of Adeleke *et al.* (2023) and Okafor *et al.* (2022), who documented analogous values for comparable biomass–coal mixtures. Pellets formulated with cassava starch, Sample 2 (10% PKS) and Sample 6 (20% PKS), demonstrated moderate calorific values ranging from 16.10 to 17.00 MJ/kg. This decline corresponds with findings by Erokare *et al.* (2025) and Sarker *et al.* (2023) who observed that starch-based binders reduce energy density due to their intrinsically lower calorific value. Polystyrene as a binder produced variable outcomes: it enhanced calorific output in 10% PKS blends (Sample 3: 18.11 MJ/kg) but significantly reduced it in 20% PKS blends

(Sample 7: 13.50 MJ/kg). This disparity aligns with findings by Zhang *et al.* (2023) and Erokare *et al.* (2026) who reported that plastic-derived binders improved low-biomass formulations while hindering combustion in higher-biomass mixtures. The wastepaper binder exhibited the lowest energy values at both blend ratios, with Sample 4 at 15.09 MJ/kg and Sample 8 at 12.07 MJ/kg. This tendency aligns with the findings of Trivedi *et al.* (2024), who determined that cellulose-rich binders are inadequate for high-energy pellet synthesis.

The findings show that the calorific value performance of the control samples was high (19.98–21.06 MJ/kg). Waste paper (WP) showed a moderate energy content (18.11 MJ/kg with 10% PKS) compared to other binder-enhanced compositions, whereas polystyrene (SF) resulted in the greatest loss (12.07 MJ/kg with 20% PKS), making it less suitable for energy-intensive industrial applications. However, the kind of binder significantly affects pellet fuel quality, with optimal performance dependent on both binder choice and biomass ratio. Notwithstanding variability, the calorific values reported herein fall within the 15.41–19.52 MJ/kg range documented by Erol *et al.* (2010) for diverse biomass fuels, thereby affirming the appropriateness of these co-fired PKSC pellets for power-generating applications.

Table 2 Calorific values of co-fired pellets (PKSC)

Pellets (10% 90%)	Calorific Value (MJ/Kg)	Pellets (20% 80%)	Calorific Value (MJ/Kg)
Sample 1	19.98	Sample 5	21.06
Sample 2	16.10	Sample 6	17.00
Sample 3	18.11	Sample 7	13.50
Sample 4	15.09	Sample 8	12.07

PKSC = Palm kernel shell Coal

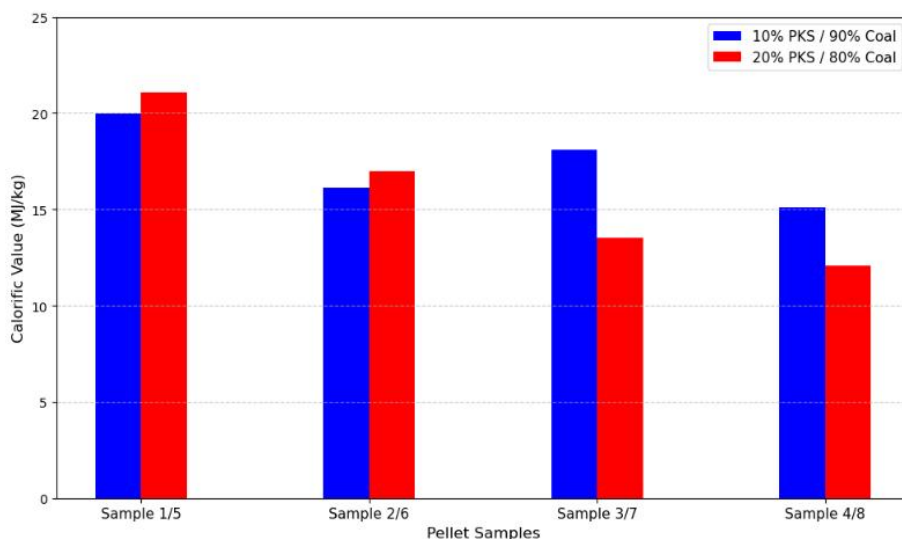


Figure 3: Calorific values of PKSC Co-fired pellets (10% 20%).

3.2 Proximate Analysis of Co-fired Pellets (Palm Kernel Shell and Coal)

This section examines the proximate composition of fuel pellets derived from mixtures of Palm Kernel Shell (PKS) and coal, both with and without binders. Two blend ratios were analysed: 10% PKS with 90% coal (PKSC 10:90) and 20% PKS with 80% coal (PKSC 20:80). Tables 3 and 4, along with Figures 4 and 5, demonstrate the impact of various binders on critical fuel parameters such as moisture, volatile matter, ash, and fixed carbon content.

3.2.1 Proximate Analysis of PKSC (10:90) Pellets

The binder type considerably influenced all evaluated parameters in the 10% PKS mix (Samples 1–4). The minimum moisture content was observed in pellets containing a polystyrene binder (Sample 3, 1.34%), whereas the control sample, devoid of a binder, exhibited the highest moisture content (Sample 1, 2.73%). This tendency validates Song and Hall's (2020) research, which demonstrates that polymeric, hydrophobic binders can diminish moisture absorption in composite biomass-coal

fuels. The volatile matter increased with the addition of the binder, peaking at 44.32% with cassava starch (Sample 2). This increase aligns with Sinebe et al., (2026) and Guo *et al.* (2023), who found that organic binders release additional volatile substances during thermal degradation.

From Table 3 and Fig. 4, a significant discovery was the considerable reduction in ash content with the application of binders. The control sample (Sample 1) exhibited an ash content of 18.36%, whereas the ash content of pellets bonded with cassava starch, Styrofoam, and wastepaper decreased to 13.08%, 15.04%, and 11.95%, respectively. The wastepaper binder exhibited the lowest ash level (Sample 4), corroborating the "ash dilution" theory via the incorporation of low-ash organic components, as observed in research on cellulose-based fuel additives (Guo *et al.*, 2023). Consequently, fixed carbon rose from 40.57% in control to a maximum of 45.66% in wastepaper-bound pellets (Sample 4). The enhancement in fixed carbon, indicative of energy density, aligns with research demonstrating that fibrous and organic binders

improve carbon retention in solid fuels (Olugbade *et al.*, 2019).

Table 3 Proximate Analysis of co-fired pellets (PKSC 10% 90%)

Proximate Analysis	Sample 1	Sample 2	Sample 3	Sample 4
% Moisture Content	2.73	1.66	1.34	198
% Volatile Matters	38.34	44.32	39.39	40.41
% Ash Content	18.36	13.08	15.04	11.95
% Fixed Carbon	40.57	40.97	44.23	45.66

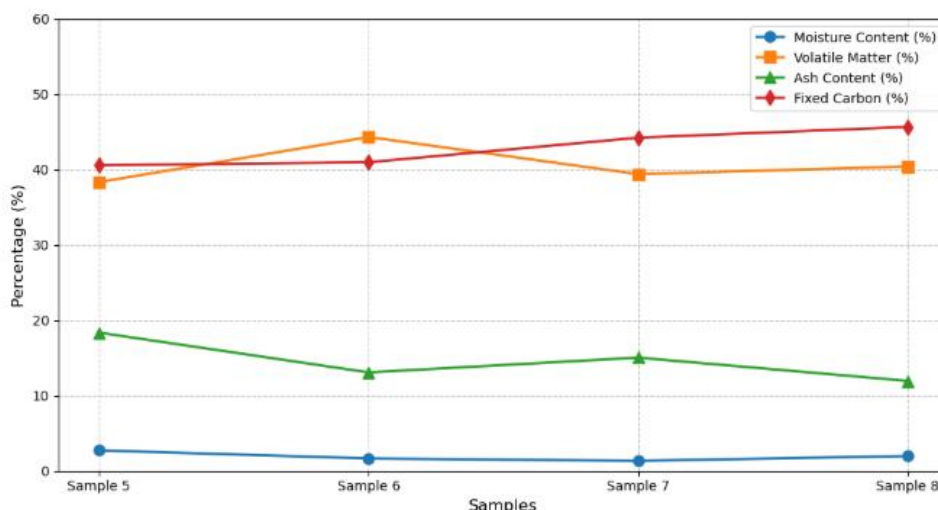


Figure 4: Proximate Analysis of Co-fired pellets (PKSC 10% 90%)

3.2.2 Proximate Analysis of PKSC (20:80) Pellets

The results for the 20% PKS blend (Samples 5–8), as illustrated in Table 4 and Fig. 5, further illustrate the influence of the binder while indicating the increased biomass proportion. The moisture content was minimal with the cassava starch binder (Sample 6, 1.81%) and maximal in the binderless control (Sample 5, 3.04%). The increased moisture in the PKSC 20:80 control compared to the 10:90 control corresponds to the higher inherent hygroscopicity of biomass materials, as noted by Ahmad *et al.* (2022)

Volatile matter was highest in wastepaper-bound pellets (Sample 8, 44.40%) and lowest in Styrofoam binder (Sample 7, 32.66%). This variance indicates intricate, non-linear interactions among the binder, biomass, and

coal during heating, shaped by the unique thermal degradation characteristics of each component, as reported by Guo *et al.* (2023). The use of binders significantly decreased ash content, particularly in cassava starch (Sample 6, 10.59%) and wastepaper (Sample 8, 12.48%), compared with the control (19.72%). This reduction supports Wang *et al.* (2020) in their investigation of pelletizing hydrochar biofuels with organic binders, reporting that organic binders reduce the ash load characteristic of biomass-coal mixtures.

The fixed carbon content exhibited a similar trend, with the peak level observed with the cassava starch binder (Sample 6, 43.70%). This outcome, along with its low ash content, demonstrates that cassava starch is particularly efficient at increasing the combustible percentage in the 20:80 mixture. The data

indicate that binder performance depends on the feedstock ratio, underscoring the importance of customized formulation in fuel engineering (Sinebe et al., 2026; Onochie et al., 2025).

The findings indicated that both biomass-coal co-fired pellet combinations have a much lower ash concentration when binders are added to PKS-coal co-fired pellets. Compared with the control binderless pellets, there was a notable 46% decrease in cassava starch (CST). In 10% Table 4 Proximate Analysis of co-fired pellets (PKSC 20% 80%)

mix ratio blends, the ash composition drops from 18.36% to 13.08%, while in 20% PKS blends, it drops from 19.72% to 10.59%. As a binder, cassava starch has the best qualities: it efficiently regulates moisture, maintains sufficient calorific value, reduces sulfur emissions, significantly reduces ash, and increases fixed carbon. Compared with burning pure coal, the 20% biomass inclusion with a cassava starch binder shows a more pronounced decrease in CO₂ and SO₂ emissions.

Proximate Analysis	Sample 5	Sample 6	Sample 7	Sample 8
% Moisture Content	3.04	1.81	1.73	2.86
% Volatile Matters	40.28	43.96	32	44.40
% Ash Content	19.72	10.59	15.73	12/48
% Fixed Carbon	37.58	43.70	39.91	40.26

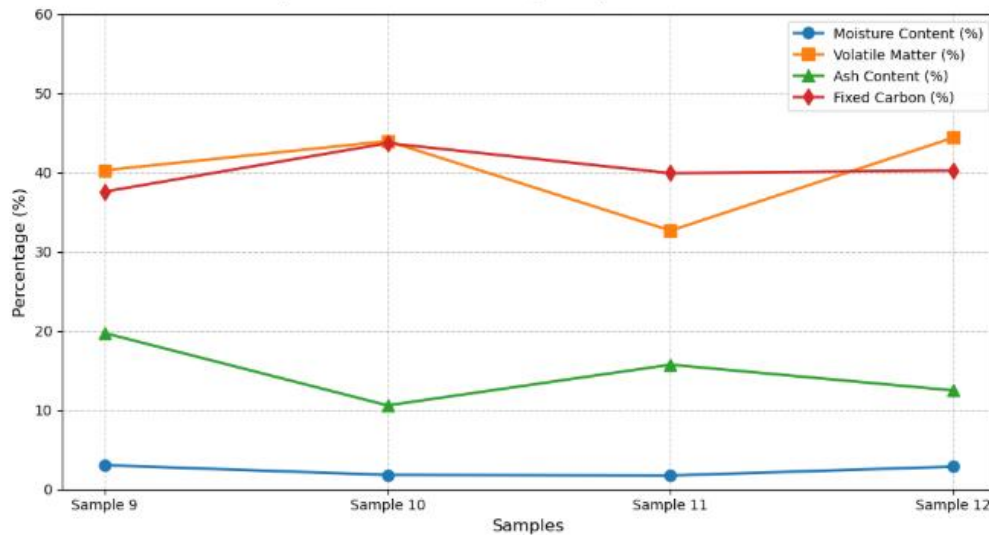


Figure 5: Proximate Analysis of Co-fired pellets (PKSC 20% 80%)

3.3 Ultimate Analysis of Co-fired Pellets (Palm Kernel Shell and Coal)

This section provides a comprehensive elemental analysis of fuel pellets made from palm kernel shell (PKS) and coal, with and without binders. Trivedi *et al.* (2024) mentioned that the elemental composition

comprises carbon (C), hydrogen (H), nitrogen (N), sulphur (S), and oxygen (O), which are crucial for assessing heating value, combustion characteristics, and potential emissions. Data for two mixture ratios, 10% PKS and 90% coal (PKSC 10:90), and 20% PKS and 80% coal (PKSC 20:80), are presented in Tables 5 and 6

and illustrated in Figs. 6 and 7, respectively. This assessment elucidates how cassava starch, Styrofoam, and wastepaper binders chemically alter the fuel composition.

3.3.1 Ultimate Analysis of PKSC (10:90) Pellets

The addition of a binder to the 10% PKS mix resulted in significant changes in the elemental composition. The carbon concentration varied considerably among the samples. The pellets bound with Styrofoam (Sample 3) had the highest carbon content at 60.20%, followed closely by those made with wastepaper (Sample 4), which had a carbon concentration of 57.56%. The control (Sample 1) and cassava starch-bound pellet (Sample 2) exhibited lower levels of 50.18% and 48.98%, respectively. The elevated carbon input from Styrofoam and wastepaper is attributable to their inherent carbon content, which aligns with the findings of Umubigho *et al.*, (2026), Onochie *et al.* (2024) and Guo *et al.* (2023), hence augmenting the carbon sourced from coal and PKS and improving energy potential. The reduced carbon content of cassava starch can be attributed to its oxygen-rich molecular composition, which decreases the relative carbon content on a mass basis, as indicated by Olugbade *et al.* (2019). The hydrogen level was elevated with the incorporation of binders,

particularly Styrofoam (Sample 3, 5.05%) and cassava starch (Sample 2, 4.63%), compared with the control (3.33%). Hydrogen is pivotal in fuel volatility and combustion velocity. The increased hydrogen content in polystyrene aligns with its hydrocarbon-based polymer chemistry, which releases extra hydrogen during heat degradation, as noted by Song and Hall (2020) in their study. The sulphur content, a principal source of pollution, showed an increasing trend with the application of binders: 0.57% (control), 0.64% (cassava starch), 0.71% (Styrofoam), and 0.85% (wastepaper). The rise in wastepaper underscores the need to assess emission trade-offs when choosing binders for energy optimisation. The control sample demonstrated the minimal sulphur content (0.41%). The oxygen content was minimal in the cassava starch-bound pellet (Sample 2, 2.51%), an unforeseen outcome given the usual starch composition, potentially attributable to specific interactions during processing. The control sample exhibited the highest oxygen concentration (5.47%). The nitrogen content remained consistently low and stable (1.38–1.53%) across all formulations, indicating that nitrogen introduction is not a significant issue with these binder types, as observed by Wang *et al.* (2020).

Table 5 Ultimate Analysis of co-fired pellets (PKSC 10% 90%)

Ultimate Analysis	Sample 1	Sample 2	Sample 3	Sample 4
% Sulphur Content	0.57	0.64	0.71	0.85
% Carbon Content	50.18	48.98	60.20	57.56
% Oxygen Content	4.28	3.10	2.98	2.49
% Nitrogen Content	1.45	1.46	1.40	1.48
% Hydrogen Content	3.33	4.63	5.50	4.22

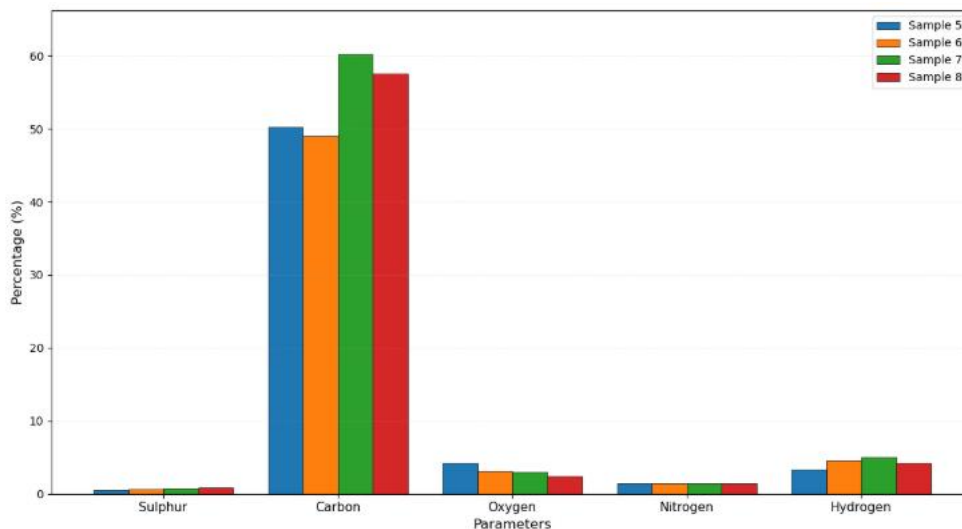


Figure 6: Ultimate Analysis of co-fired pellets (PKSC 10% 90%)

3.3.2 Ultimate Analysis of PKSC (20:80) Pellets

The results for the 20% PKS blend (Samples 5–8) further demonstrate the influence of the binder while indicating the increased biomass proportion. The carbon concentration was maximal with the polystyrene binder (Sample 7, 70.28%) and minimal with cassava starch (Sample 6, 43.52%). This indicates a synergistic effect wherein the polymeric binder efficiently holds carbon from both coal and PKS. Conversely, cassava starch had the lowest carbon content (Sample 6, 43.52%), aligning with the findings of Olugbade *et al.* (2019), which suggest this is attributable to its elevated oxygen concentration and comparatively less carbon contribution. The hydrogen content showed a similar trend, with polystyrene producing the highest concentration (Sample 7, 6.65%). The increased hydrogen content, coupled with high carbon levels, signifies a fuel with enhanced combustion characteristics and energy density. The control sample had the lowest hydrogen level (2.28%), highlighting the substantial impact of the polystyrene binder. The sulphur concentration increased with the incorporation of binders, notably in waste

paper (Sample 8, 1.00%) and Styrofoam (Sample 7, 0.75%), underscoring the need to assess emission trade-offs when choosing binders for energy optimisation. The control sample demonstrated the minimal sulphur content (0.41%). The oxygen content was minimal in the cassava starch-bound pellet (Sample 6, 2.51%), an unforeseen outcome given the usual starch composition, potentially attributable to specific interactions during processing. The control sample exhibited the highest oxygen concentration (5.47%). The nitrogen content remained consistently low and stable (1.25–1.46%) across all formulations, indicating that nitrogen introduction is not a significant issue with these binder types, as noted by Wang *et al.* (2020).

The results indicate distinct variations in fuel composition attributable to the type of binder used. Cassava starch increases carbon, hydrogen, and oxygen levels while slightly decreasing sulphur levels, indicating higher energy density and cleaner combustion. Polystyrene offers optimal improvements in carbon and hydrogen while exerting a low sulphur influence, which is beneficial for volatility and flame propagation. Wastepaper

provides the most significant carbon enrichment; however, it also introduces elevated sulphur levels due to impurities, underscoring the need for pretreatment. The variations illustrate that selecting a binder can alter the elemental composition, thereby influencing combustion efficiency, calorific value, and emissions in thermal processes (Song & Hall, 2020; Guo *et al.*, 2023; Lomunyak *et al.*, 2024).

Table 6 Ultimate Analysis of co-fired pellets (PKSC 20% 80%)

Ultimate Analysis	Sample 5	Sample 6	Sample 7	Sample 8
% Sulphur Content	0.41	0.63	0.75	1.00
% Carbon Content	54.03	43.52	70.28	58.50
% Oxygen Content	5.47	2.51	3.02	3.24
% Nitrogen Content	1.36	1.25	1.40	1.46
% Hydrogen Content	2.28	3.53	6.65	4.32

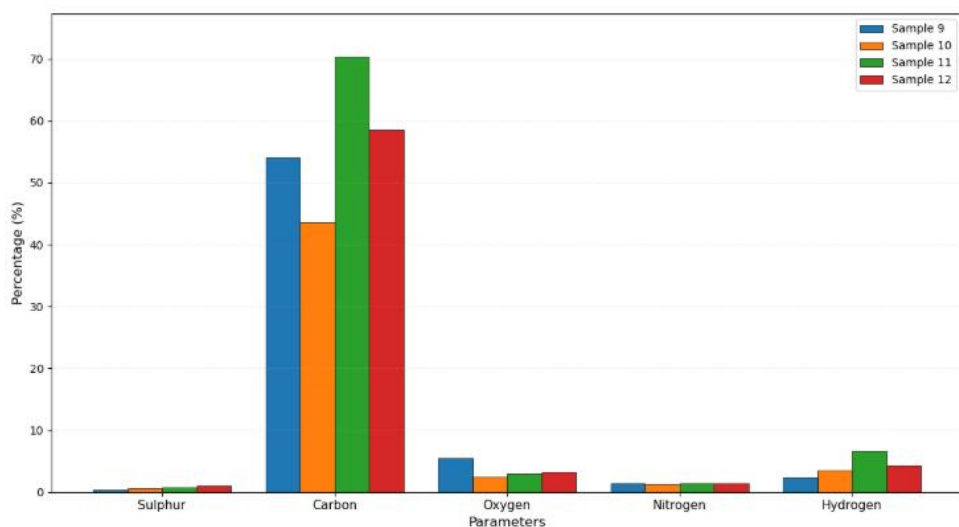


Figure 7: Ultimate Analysis of co-fired pellets (PKSC 20% 80%)

6. Conclusion

The study offers a thorough explanation of the impact of binders on the parameters of biomass-coal fuel pellets and their environmental performance. The research indicates that binder selection is a significant determinant that affects not only the mechanical properties of pellets but also determines the ash content, energy profile, and emission characteristics. The experiment

revealed that cassava starch is an ideal binder for palm kernel shell coal at both 10% and 20% mix ratios for co-firing applications. It increases the fixed carbon content and significantly decreases the ash content, making it more advantageous for reducing sulphur oxide emissions. The wastepaper binder elevates both carbon and sulphur levels, attributed to impurities in the wastepaper, which necessitate pretreatment before

application. Polystyrene binders exhibit significant hydrophobicity; however, they significantly reduce calorific value and increase sulphur content, rendering them inappropriate for energy production. This investigation revealed that a 20% inclusion of palm kernel shell combined with a cassava starch binder constitutes an ideal composition, resulting in a notable 10.59% ash reduction and an acceptable calorific value of 17.00 MJ/Kg, with implications for emission reductions. It also exhibited promising reductions in combustion emissions. This research establishes validation parameters for the development of sustainable binder-enhanced fuel pellets, serving as a dependable thermal energy source to replace fossil fuels and as a cost-effective, environmentally sustainable waste disposal method for agro-waste management and emission reduction in coal-dependent areas.

Acknowledgements The authors acknowledge the technical support provided by the Department of Mechanical Engineering, Delta State University, Abraka, Nigeria and Tamale Technical University, Ghana.

Author's Contributions

E. T. Erokare: Conceptualization, methodology, investigation (sample collection, pelletization, and laboratory characterization), formal analysis (calorific, proximate, and ultimate data interpretation), writing – original draft preparation and corresponding author duties. **M. Ekpu:** Supervision, project administration, validation of experimental results, resources (provision of laboratory facilities at Delta State University), review & editing. **J.E. Sinebe:** Supervision, project administration, validation of analytical methods. **S.O. Sada:** Conceptualization support, formal analysis (interpretation of

proximate/ultimate combustion properties). **S.C. Ikpeseni:** Investigation (assisted with sample preparation and binder formulation), statistical analysis, and writing – review & editing. **A.M. Atsu:** Resources (provided access to X-ray fluorescence and calorimetry equipment at Tamale Technical University), validation of elemental analysis data, and writing – review & editing (international collaboration).

References

- Adeleke, A. A., Petrus, N., Ayuba, S., Yahya, A. M., Ikubanni, P. P., Okafor, I. S., Emmanuel, S. S., Olosho, A. I., & Adesibikan, A. A. (2023). Nigerian biomass for bioenergy applications: A review on the potential and challenges. *Journal of Renewable Materials*, 11(12), 4123–4141.
- Ahmad, R. K., Sulaiman, S. A., Yusup, S., Dol, S. S., Inayat, M., & Umar, H. A. (2022). Exploring the potential of coconut shell biomass for charcoal production. *Ain Shams Engineering Journal*, 13(1), 101499.
- Al-Qayim, K., Nimmo, W., Hughes, K. J., & Pourkashanian, M. (2019). Effect of oxy-fuel combustion on ash deposition of pulverized wood pellets. *Biofuel Research Journal*, 21, 927–936.
- Anguruwa, G. T., Yaduma, Z. B., Odega, C. A., Fatade, B. O., Ademola, T., & Omidiran, M. O. (2024). Characterization of briquette derived from three wood residues using starch as binder. *Journal of Forestry Research and Management*, 21(2), 126–139.
- Baxter, L. (2005). Biomass-coal co-combustion: Opportunity for affordable renewable energy. *Fuel*, 84, 1295–1302.
- Chen, W. H., Peng, J., & Bi, X. T. (2015). A state-of-the-art review of biomass torrefaction, densification and applications. *Renewable and*

- Sustainable Energy Reviews*, 44, 847–866.
- Erokare, E. T., Umunna, M. F., Efe, J. I., Nyorere, O., Iweka, S. C., Okoh, P. C., & Ikoko, O. (2025). Suitability of cassava starch and waste paper binders for biomass pellets: A review study. *Nigerian Journal of Engineering Technology and Science Education*.
- Erokare, ET; Ekpu, M; Sinebe, JE; Sada, SO; Ikpeseni, SC; Atsu, AM (2026). A critical review on the impacts of binder on pellet quality, combustion performance and pollutant emissions in biomass-coal co-fired pellets. *Journal of Applied Sciences and Environmental Management*, 30(5), 1663–1673.
- Erokare, ET; Ekpu, M; Sinebe, JE; Sada, SO; Ikpeseni, SC; Atsu, AM (2026). Combustion performance and emission characteristics of sawdust-coal pellets using waste styrofoam as binder. *Journal of Science Innovation & Technology Research (JSITR)*. <https://doi.org/10.70382/ajsitr.v12i9.072>
- Erol, M., Haykiri-Acma, H., & Küçükbayrak, S. (2010). Calorific value estimation of biomass from their proximate analyses data. *Renewable Energy*, 35(1), 170–173.
- Fernando, R. (2012). *Co-firing high ratios of biomass with coal (CCC/194)*. International Centre for Sustainable Carbon. Retrieved from <https://www.sustainable-carbon.org/report/cofiring-high-ratios-of-biomass-with-coal-ccc-194/>
- Guo, X., Zhang, H., & Wang, Y. (2023). Synergistic ash reduction and emission control in coal-biomass blends using polymer additives. *Fuel*, 352, 129104.
- Ighodaro, O. O., & Ndem, F. E. (2023). Performance modelling of co-fired palm kernel shell pulverized coal blend in a steam power plant. *Journal of Applied Sciences and Environmental Management*, 27(5), 899–903.
- International Energy Agency. (2025). *World Energy Outlook 2025*. Paris: IEA.
- International Renewable Energy Agency. (2024). *Global Energy Transformation: A Pathway to 2030*. Abu Dhabi: IRENA.
- Sinebe, J. E., Erokare, E., Ulakpa, W. C., Bereprebofa, D., & Enyi, C. L. (2026). Comparative evaluation of fuel properties and energy potential of pellets produced from diverse agricultural biomass wastes in tropical regions: Implications for sustainable bioenergy production. *FUDMA Journal of Sciences*, 10(10), 244–250. <https://doi.org/10.33003/fjs-2026-1010-5460>
- Sinebe, J. E., Erokare, E. T., Ulakpa, W. C., Bereprebofa, D., & Enyi, C. L. (2026). Comparative emission potential assessment of coconut shell–coal pellets using ultimate analysis for sustainable co-firing applications. *Umudike Journal of Engineering and Technology*, 12(3), 20–28. https://doi.org/10.33922/j.ujet_v12i3_3
- Sinebe, J. E., Erokare, E. T., Ulakpa, W. C., Bereprebofa, D., & Enyi, C. L. (2026). Effect of optimization ratios on proximate and ultimate compositions and heating values of palm kernel shell and groundnut shell co-fired pellets bound with wastepaper. *Journal of Applied Sciences and Environmental Management*, 30(8), 2470–2479. <https://dx.doi.org/10.4314/jasem.v30i8.6>
- Kolo, Z. K., Musa, M. A., & Jones, A. N. (2024). Effect of binders on the performance of charcoal briquettes produced from selected biomass. *Arid Zone Journal of Engineering Technology and Environment*, 20(1), 1–10.

- Kuswa, F. M., Putra, H. P., Prabowo, Guntur, H. L., Ghazidin, H., Darmawan, A., Ali Nandar, C. S., Aziz, M., Ding, L., & Haryana, H. (2025). Evaluation for the combination of oil palm biomass as co-firing fuel: Investigation into ash-related problems. *Biomass Conversion and Biorefinery*, 15, 10537–10551.
- Lomunyak, G., Osodo, B., Njoka, F., & Kombe, E. (2024). Characterization, optimization, and emission analysis of manually-made charcoal dust briquettes with starch, paper, and algae binders. *Heliyon*, 10(24), e40991.
- Nainggolan, I. F., Hadiyanto, & Utomo, M. S. K. T. (2023). Performance analysis of co-firing using palm kernel shells in a chain grate stoker coal-fired power plant 2 × 7 MW. *Briliant*, 8(2). <http://dx.doi.org/10.28926/briliant.v8i2.1349>
- Okafor, C., Nzekwe, C., Ajaero, C., Ibekwe, J., Otunomo, F., Charles, C., Juliet, C., & Festus, A. (2022). Biomass utilization for energy production in Nigeria: A review. *Clean Energy Systems*, 3, 100043.
- Olugbade, T., Ojo, O., & Mohammed, T. (2019). Influence of binders on combustion properties of biomass briquettes: A recent review. *BioEnergy Research*, 12, 51–68.
- Orhorhoro, E. K., Oyejide, J. O., & Erokare, T. E. (2023). Optimization of biogas yield by the combination of algal biomass and food waste. *NIPES Proceedings in Science & Technology*, 2(3), Article 44. <https://doi.org/10.37933/nipesproc/3.2.2023.44>
- Onochie, U. P., Obanor, A. I., Aliu, S. A., & Igbodaro, O. O. (2017). Proximate and ultimate analysis of fuel pellets from oil palm residues. *Nigerian Journal of Technology*, 36(3), 987–990.
- Onochie, U. P., Otomi, K. O., Owamah, H. I., Ikpeseni, S. C., & Adingwupu, A. C. (2022). Assessment of power generation potential from the co-firing of *Elaeis Guineensis* residues with coal pellets in a popular Nigerian palm oil research institute. *International Journal of Coal Preparation and Utilization*, 42(9), 2804–2819.
- Onochie, U. P., Ofomatah, A. C., Owamah, H. I., Ikpeseni, S. C., Onwusa, S. C., Erokare, T. E., & Orugba, H. O. (2024). Assessment of the compatibility of biomass-coal blends for cleaner energy utilization and sustainable development. *Biomass Conversion and Biorefinery*. <https://doi.org/10.1007/s13399-024-05771-3>
- Onochie, U. P., Ekanem, D. O., Onoroh, F., Osigbeme, M. S., Owamah, H. I., Orugba, H. O., Ikpeseni, S. C., Okolotu, G. I., Oyeibisi, S., & Kwasi-Effah, C. C. (2025). Palm kernel shell and coconut shell pellets cofiring: Effect of optimization ratio on the combustion emission CO₂ and SO₂. *NIPES Journal of Science and Technology Research*, 7(2), 85–104. <https://doi.org/10.37933/nipes/7.2.2025.6>
- Peng, J. H., Bi, X. T., Sokhansanj, S., & Lim, C. J. (2013). Torrefaction and densification of different species of softwood residues. *Fuel*, 111, 411–421.
- Pradhan, P., Mahajani, S. M., & Arora, A. (2018). Production and utilization of fuel pellets from biomass: A review. *Fuel Processing Technology*, 181, 215–232.
- Sarker, P. R., Borugadda, V. B., Meda, V., & Dalai, A. K. (2023). Optimization of pelletization process conditions and binder concentration for production of fuel pellets from oat hull and quality evaluation. *Biomass and Bioenergy*, 174, 106825.
- Song, B., & Hall, P. (2020). Densification of biomass and waste plastic blends as a solid fuel: Hazards, advantages, and

- perspectives. *Frontiers in Energy Research*, 8, 58.
- Trivedi, K., Sharma, A., Kanabar, B. K., Arunachalam, K. D., & Gautam, S. (2024). Comparative analysis of coal and biomass for sustainable energy production: Elemental composition, combustion behavior, and co-firing potential. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11270-024-07509-3>
- Umubigho, W., Ekpu, M., Sada, S. O., Sinebe, J. E., & Ikpeseni, S. C. (2025). Characterising emissions from sawdust-coal pellets combustion using ultimate analysis techniques. *NIPES Journal of Science and Technology Research*, 7(1), 64–81. <https://doi.org/10.37933/nipes/7.1.2025.6>
- Umubigho, W., Sinebe, J. E., Erokare, E. T., & Ulakpa, W. C. (2026). Experimental investigation of the thermal performance of coal–sawdust fuel pellets with varying biomass ratios. *Journal of African Innovation & Advanced Studies*, 12(2), 296. <https://doi.org/10.70382/ajaias.v12i2.082>
- United Nations Environment Programme. (2024). *Emissions Gap Report 2024*. Nairobi: UNEP.
- Vamvuka, D., Pasadakis, N., Kastanaki, E., Grammelis, P., & Kakaras, E. (2003). Kinetic modeling of coal/agricultural by-product blends. *Energy & Fuels*, 17(3), 549–558.
- Wang, Z., Zhai, Y., Wang, T., Wang, B., Peng, C., & Li, C. (2020). Pelletizing of hydrochar biofuels with organic binders. *Fuel*, 280, 118659. <https://doi.org/10.1016/j.fuel.2020.118659> [Get rights and content](#)
- World Bank. (2024). *Energy Sector Directions Paper: 2024 Update*. Washington, DC: World Bank.
- Yaka, H., Insel, M. A., Yucel, O., & Sadikoglu, H. (2022). A comparison of machine learning algorithms for the estimation of higher heating values of biomass and fossil fuels from ultimate analysis. *Fuel*, 320, 123971.
- Zhang, Y.-L., Kang, J.-N., Dai, M., Hou, J.-J., Liu, L.-C., Wei, Y.-M., & Liao, H. (2023). The role of BECCS technology in achieving carbon neutrality: Evidence from China's coal power sector. *Environment, Development and Sustainability*. <https://doi.org/10.1007/s10668-023-03842-5>