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Combustion Performance and Emission Characteristics of Sawdust-Coal Pellets Using Waste Styrofoam as Binder

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Abstract

Managing municipal solid waste remains a major environmental challenge, particularly due to persistent non-biodegradable materials, such as expanded polystyrene (Styrofoam), and underutilised biomass, such as sawdust. While Styrofoam contributes to environmental pollution, sawdust offers significant but largely untapped energy potential. This study investigates the role of Styrofoam in sawdust–coal pellets as an energy-dense binder that causes a dilution or concentration effect depending on the baseline biomass-coal mixing matrix, aiming to enhance fuel quality while assessing associated emission trade-offs. Six pellet formulations were developed, including sawdust–coal blends (10:90 and 20:80) and pure coal controls, prepared with and without a 30 wt% Styrofoam binder. Pellets were fabricated using a manual screw press, sun-dried, and characterised via bomb calorimetry, proximate analysis, and X-ray fluorescence. Stoichiometric combustion modelling and Python-based simulations were applied to estimate flue gas compositions. Results indicate that the addition of Styrofoam increased the calorific value by 8.3–20.2% (up to 22.72 MJ/kg), reduced the moisture content to 0.95%, and increased the carbon and volatile matter contents. Although sulphur content rose slightly (0.67–1.11%), SO_2 emissions remained low and within acceptable limits. Overall, Styrofoam-enhanced pellets demonstrated improved energy performance with manageable emissions, supporting their potential for sustainable waste-to-energy applications.

Keywords: Waste-to-Energy (WtE), Styrofoam Binder, Sawdust-Coal Pellets, Combustion Emissions, SO_2 Modeling.

Introduction

The management of municipal solid waste presents a global environmental challenge, particularly for persistent materials like expanded polystyrene (Styrofoam) and abundant biomass residues such as sawdust. These waste streams are often underutilised or improperly managed. Expanded polystyrene (EPS) debris, also known as styrofoam, has become a significant environmental concern in recent years due to its persistent presence in natural ecosystems and its non-biodegradable nature (Febriansya *et al*., 2024; Mekbuntoon, *et al*., 2023; Evode *et al*., 2021). Its non-biodegradable nature endangers the environment by increasing visual pollution, disrupting ecosystems, and possibly posing health risks to a variety of plant and animal species. Consequently, there is an increasing need to understand the negative environmental impacts of Styrofoam waste and to identify sustainable ways to manage it (Febriansya *et al*., 2024; Kumar *et al*., 2021; Moshood *et al*., 2022). Erokare *et al*. (2025) reported that waste from different wood samples (sawdust) had a moisture content ranging from 7.26% to 7.70%. Similarly, the waste samples had high calorific values, ranging from 30,516.81 kJ/kg to 30,738.38 kJ/kg. Additionally, the combustion performance of the sawdust samples showed that the amount of carbon (IV) oxide released to the atmosphere during combustion is exceptionally low (18% to 22%). Therefore, instead of being disposed of and potentially contaminating our environment, biomass coal fuel pellets could be formed by co-densifying multiple waste materials with coal, such as sawdust and Styrofoam as a binder, which has emerged as a promising strategy for waste valorisation and energy recovery. This approach transforms problematic wastes into a value-added solid fuel, addressing both disposal needs and the demand for alternative energy sources (Dorokhov et al, 2024).

The fundamental advantage of biomass coal fuel pellets lies in their ability to combine materials with complementary properties. Biomass residues typically have moderate heating values, while certain plastics offer higher energy content and can act as binding agents, as reported by Adesina et al. (2025. When combined, these materials can achieve favourable energy densities with coal. There is growing interest in coal-blend technologies, representing a transitional strategy toward cleaner energy systems. Research on sawdust-coal pellets has demonstrated that increasing the biomass content progressively reduces carbon dioxide (CO_2) emissions (Umubigho et al, 2025). However, this environmental benefit is accompanied by complex trade-offs in emissions. Counterintuitively, one study found that sulphur dioxide (SO_2) emissions increased with higher sawdust content, peaking in pellets composed of 100% sawdust (Umubigho et al., 2025). This was

attributed to the specific sawdust used having a higher inherent sulphur content (7.12%) than the coal (0.51%) in that study, resulting in SO_2 emissions ranging from 0.03% to 0.29% in the dry analysis (Umubigho et al., 2025). This highlights a critical paradox: while biomass addition generally reduces greenhouse gas emissions, it can simultaneously increase acid gas emissions depending on the feedstock's composition. Conversely, other research indicates that adding wood sawdust (30%) to coal-based pellets can reduce sulphur oxide (SOx) concentrations by 25% per unit of heat released, suggesting chemical interactions during combustion can also promote sulphur retention (Klepikov et al., 2020). Onochie et al. (2025) reported contradictory findings, underscoring that emission profiles are highly dependent on the specific materials and combustion conditions. Within this context, polystyrene (Styrofoam) is an exciting component for biomass-coal fuel pellet formulation due to its potential dual role. As a binder, it can improve the mechanical strength and durability of pellets. However, the effects on the physicochemical and emission properties are yet to be fully harnessed; plastics often contain sulphur-containing additives from manufacturing, meaning polystyrene could also act as a sulphur source during combustion. (Butler et al., 2023).

This dual functionality creates a specific research interest: the emission trade-offs associated with using polystyrene as a binder in sawdust-coal systems are not well understood. Key questions include how the binding benefits weigh against potential sulphur emissions, and what synergistic effects occur when polystyrene is combined with biomass coal of varying sulphur content. This paper seeks to address these questions through a focused investigation of "Emission Trade-offs in Sawdust-Coal Pellet Combustion: The Dual Role of Styrofoam as Binder and Sulphur Source." By systematically analysing the interactions between Physicochemical composition and combustion emissions, six (6) samples of biomass coal pellets will be produced in optimised mix ratios of 10% sawdust, 90% coal, 20% sawdust, 80% coal, 100% coal and Styrofoam binder as 30% of the total biomass coal weight. The findings will provide insights into optimising biomass-coal pellet fuel formulations that balance waste valorisation benefits with minimal environmental impact.

Materials and Methods

Materials

Collection and Preparation of Samples: The lumps of coal were obtained from the Ogui coal dump site in Enugu North Local Government Area of Enugu State. The sample was sun-dried for a week to reduce moisture content and facilitate pulverisation. Figure 1a shows a lump of coal sample, and Figure 1b shows a pulverised coal sample. The Sawdust was sourced from a waste dump site at Ogbosisi market in Asaba, Delta State. The Sawdust was sorted to remove wood lumps and was sundried for five (5) days to reduce its moisture content and ease grindability. Figure 2a: Sawdust sample before grinding, and Figure 2b: after grinding. Styrofoam samples were collected at an electronics market dump site in Onitsha, Anambra State. The Styrofoam’s were dissolved in premium motor spirit to form a paste (binder), which

was then used. Due to the highly volatility of premium motor spirit used to dissolve the Styrofoam, the produced pellets were aired in open and dry aerated place to enable the premium motor spirit to evaporate from the pellets before taken for analysis. Figure 3a shows Styrofoam in the solid state, and Figure 3b shows it in the binder form.



Figure 1a Coal Lump



Figure 1b Pulverised Coal



Figure 2a Sawdust



Figure 2b Pulverised Sawdust



Figure 3a Styrofoam

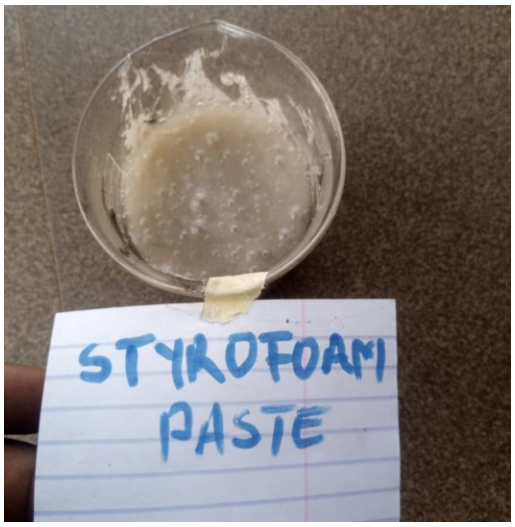


Figure 3b Styrofoam Paste

Methods

Preparation of Biomass Coal pellet Samples

According to research reports of several authors (Umubigho *et al*, 2025; Onochie *et al*, 2024; Ighodaro & Ndem, 2023; Onochie *et al*, 2022; Wang *et al*, 2020; Al-Qayim *et al*, 2019; Fernando *et al*, 2012; Baxter, 2005; Vamvuka *et al*, 2003), 10% and 20% are optimum mixing ratios, especially for co-fired biomass-coal pellets applications. These ratios were used to produce pellets, with 30% of the total sample weight used for the binder mix; this binder mix falls within the range reported by Kolo et al. (2024) and Anguruwa et al. (2024) for briquetting samples used for heating and power generation. For the research, the binding material is Styrofoam, which is used to prepare pellets before characterisation analysis. As shown in Table 1. To guarantee the accuracy of the results, the analyses were carried out for two (2) independent replicates for every sample. To take into consideration potential variations in sample preparation and measurement, each replicate was processed and examined independently.

Table 1: Components of Biomass Coal Feedstock Material Ratios

Pellets Samples	Coal (wt %)	SD (wt %)	SF (wt %)
Sample 1	90	10	00
Sample 2	90	10	30
Sample 3	80	20	00
Sample 4	80	20	30
Sample 5	100	00	00
Sample 6	100	00	30

SD = Sawdust, SF = Styrofoam.

Production of the Biomass Coal Pellet Samples

Figure 4(A-F) shows biomass coal pellets produced mechanically using a manual screw press pelletizing machine. These pellets include sawdust-coal (SDC) with Styrofoam binders as stated in Table 1. These pellets were thereafter sun-dried for 1 week to reduce moisture content and increase hardness and placed in a Ziploc bag before characterisation.



A B C D

E F

Figure 4 Biomass coal pellets produced mechanically using a manual screw press pelletizing machine Characterisation of Biomass coal Pellets Samples

Calorific values of Biomass Coal 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

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

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

w = Mass of water in the calorimeter

ΔT = rise in water temperature (^{O}C)

m = mass of fuel (g)

Proximate Analysis of the Fuel Sample

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.

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

Calculation:

$$\mathrm{VM} = \frac{(W2-W3)}{(W2-W1)} x\ 100 \quad (2)$$

W1- weight of empty crucible

W2- weight of crucible+ dry sample

W3- weight of crucible+ residue after heating

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.

Calculation: $\mathrm{AC} = \frac{(\mathrm{W2-W3})}{(\mathrm{W2-W1})} x\ 100$ (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.

Calculation: $\mathrm{MC} = \frac{(\mathrm{W2-W3})}{(\mathrm{W2-W1})} x\ 100$ (4)

W1- weight of empty container

W2- weight of container+ wet sample

W3- weight of container dry sample

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

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

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

Ultimate Analysis Fuel Sample

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 sulphur) were determined using a X-ray fluorescence (Xenemetrix 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 a thin PTFE 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.

Chemical and Combustion Performance Analysis of Co-fired Pellets

The chemical composition of co-fired pellets was determined from ultimate analysis results to provide insights into their elemental makeup for combustion assessment. This will be inserted into Equation (6)

$C_aH_bO_dN_eS_f$ (6)

The combustion analysis of biomass coal pellet samples (i.e., sawdust-coal pellets) was evaluated using Equation (7). The number of atom of carbon (a), hydrogen (b), oxygen (c), nitrogen (d) and sulphur (f) in each of the pellets samples was obtained using equation 7 and the chemical formula of the pellets are obtained from the values of p_1, q_1, r_1, and t_1. Now, since the oxygen is supplied as air, the associated N_2 will appear in the Equation as:

$$C_aH_bO_dN_eS_f + y_1\,[O_2 + (79/21)N_2] \rightarrow p_1CO_2 + q_1H_2O + r_1SO_2 + [t_1 + y_1(79/21)N_2] \quad (7)$$

Combustion Emission Analysis of -fired pellets

The results were analysed using Python (2025 version) to generate various graphs and other useful statistics. A comparative analysis of emissions (CO_2, SOx, and NOx) from co-fired pellets (wet and dry) was conducted. A percentage analysis was employed to assess differences in emissions across the different solid fuel types.

The percentage of each product emitted from the stoichiometric combustion of pellet samples 1-6 in the wet and dry emission analysis was calculated using equations 8 and 9, respectively.

For wet analysis, % $of\ gas\ emitted\ is = \frac{ni}{nCO2+nSO2+nH2O+nN2} x100$ (8)

For dry analysis, % $of\ gas\ emitted\ is = \frac{ni}{nCO2+nSO2+nN2} \times 100$ (9)

Where ni is the amount (in kmol) of the particular product of emission under consideration, and $nCO2, nSO2, nH2O, and\ nN2$ represent the amount (in kmol) of carbon dioxide, sulphur dioxide, water vapour and nitrogen gas emitted, respectively.

Results and Discussion

Calorific Values of Co-fired Pellet Samples

The calorific values of biomass-coal pellets, as shown in Table 2, are influenced by composition. Styrofoam addition consistently elevates energy content, with increases from 17.87 MJ/kg (Sample 1) to 19.98 MJ/kg (Sample 2, 11.8% rise), 16.84 MJ/kg (Sample 3) to 18.24 MJ/kg (Sample 4, 8.3% rise), and 18.90 MJ/kg (Sample 5) to 22.72 MJ/kg (Sample 6, 20.2% rise), attributable to polystyrene's high inherent heating value (often 33–46 MJ/kg). This aligns with studies by Bhattarai et al. (2023) and Garrido et al. (2017) on plastic-biomass blends, where net calorific values range from 16.6 to 20.8 MJ/kg, surpassing subbituminous coal (13.4 MJ/kg) when plastics enhance energy density. Conversely, higher sawdust proportions dilute calorific value without Styrofoam (17.87 MJ/kg in Sample 1 vs. 16.84 MJ/kg in Sample 3, 5.8% drop) and with it (19.98 MJ/kg in Sample 2 vs. 18.24 MJ/kg in Sample 4, 8.7% drop), as sawdust's lower energy (15–19 MJ/kg) offsets coal's contribution compared to pure coal (18.90 MJ/kg). Similar trends appear in the research of Akhator *et al*. 2023 and Lunguleasa *et al*. 2019 on wood waste-PET briquettes, where pure biomass yields 17.15 MJ/kg, rising with plastic inclusion. These pellets show promise for waste-derived fuels, with values competitive against typical biomass briquettes (10–13 MJ/kg) or enhanced blends (up to 24.3 MJ/kg with plastics).

Table 2: Calorific values Results of Biomass Coal Pellets

Pellets Samples	Calorific Value (MJ/Kg)
Sample 1	17.87
Sample 2	19.98
Sample 3	16.84
Sample 4	18.24
Sample 5	18.90
Sample 6	22.72

Proximate Analysis of Co-fired Pellet Samples

The proximate analysis of the biomass-coal pellets reveals key trends in fuel quality influenced by composition. The addition of Styrofoam consistently reduces moisture content, as seen in Table 3, by comparison: from 3.49% (Sample 1) to 1.55% (Sample 2), 4.56% (Sample 3) to 1.93% (Sample 4), and 2.42% (Sample 5) to 0.95% (Sample 6). This hydrophobic effect enhances combustion efficiency by minimising energy loss to evaporation, aligning with

studies on plastic additives in biomass fuels, where RDF (including plastics such as polystyrene) reduced moisture in sawdust pellets from ~11% to lower levels (Chotikhun *et al*., 2023). Volatile matter generally increases with Styrofoam incorporation, improving ignitability: rising from 40.03% to 45.09% (Samples 1 vs. 2), slightly from 43.66% to 44.06% (3 vs. 4), and markedly from 36.40% to 46.12% (5 vs. 6). Similar elevations in volatile content (up to 72% in blends) have been reported when adding plastics to sawdust, aiding rapid devolatilization (Dorokhov *et al*., 2024).

Ash content shows mixed responses to Styrofoam: minor increases in sawdust-coal blends (10.77% to 11.17%; 4.54% to 7.99%) but a decrease in pure coal (17.00% to 14.35%), suggesting dilution of mineral residues by low-ash polystyrene. This contrasts with some coal-plastic extrudates where ash decreased overall due to plastic's low inorganic content (Marais et al., 2023). Fixed carbon varies: decreases in sawdust blends (45.71% to 42.19%; 47.86% to 35.83%) but increases in pure coal (43.56% to 48.55%), indicating Styrofoam's carbon contribution in coal-dominant mixes.

Increasing sawdust proportion (10% vs. 20%) raises moisture (3.49% to 4.56%) and volatile matter (40.03% to 43.66%), lowers ash (10.77% to 4.54%), and slightly boosts fixed carbon (45.71% to 47.86%), reflecting biomass's higher organics but lower energy density compared to coal (Sample 5 at 36.40% volatile, 17.00% ash). These patterns echo biomass-coal briquette studies, in which higher biomass reduces ash but may dilute fixed carbon unless offset by additives (Adeleke et al., 2021). Overall, Styrofoam enhances low-moisture, high-volatile pellets suitable for efficient combustion, though ash management remains key for operational viability.

Table 3: Proximate Analysis results of Biomass Coal Pellets

Proximate Analysis	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
% Moisture Content	3.49	1.55	4.56	1.93	2.42	0.95
% Volatile Matters	40.03	45.09	43.66	44.06	36.40	46.12
% Ash Content	10.77	11.17	4.54	7.99	17.00	14.35
% Fixed Carbon	45.71	42.19	47.86	35.83	43.56	48.55

Ultimate Analysis of Co-fired Pellet Samples

The ultimate analysis results displayed in Table 4 show that the biomass-coal pellets highlight compositional shifts driven by Styrofoam and sawdust inclusions. Styrofoam addition markedly boosts carbon content, reflecting polystyrene's high carbon composition: from 57.52% (Sample 1) to 71.06% (Sample 2), 68.71% (Sample 3) to 76.00% (Sample 4), and 46.33% (Sample 5) to 50.12% (Sample 6). This aligns with Bhattarai et al. (2023, in their report characterisations, where polystyrene (Styrofoam) exhibits 92.57% carbon, enhancing

blends with biomass (44.7% C) and coal (71.84% C). Hydrogen content generally rises with Styrofoam (3.87% to 5.99% in Samples 1-2; 4.18% to 5.45% in 5-6), though stable or slightly declining in Samples 3-4 (3.56% to 3.53%), consistent with plastics contributing higher H (7-8% in PS variants) for improved energy density (Garrido, et al., 2017).

Oxygen levels typically decrease with Styrofoam (5.61% to 4.66%; 8.13% to 5.27%), except in pure coal (3.09% to 4.05%), mirroring biomass's higher Oxygen (40-50%) dilution offset by low oxygen plastics, the similar trend was observed in the findings of Maj, *et al*., (2025) in elemental composition of different waste properties. Nitrogen declines overall with Styrofoam (1.43% to 0.98%; 1.36% to 0.65%; 1.53% to 1.38%), reducing potential NOx emissions, similar to RDF-plastic blends with Nitrogen at 1.20%, as reported by Tihin et al. (2023) in their research findings. Sulphur shows mixed effects: increases in sawdust blends (0.74% to 0.92%; 0.75% to 1.11%), within the range of the findings of Umubigho *et al*. (2025, for the characterisation of emission properties of sawdust-coal using ultimate analysis. However, the drop from 0.73% to 0.67% S in pure coal when adding Styrofoam (PS) is almost certainly a mass-balance dilution effect. Since PS has essentially 0% sulphur (no heteroatoms in its $(C_8H_8)_n$ backbone), adding it to coal reduces the overall sulphur *fraction* even if the absolute sulphur mass stays constant. This aligns with Bhattarai et al. (2023), noting typical coal values of 1–4%.

Increasing sawdust from 10% to 20% elevates carbon (57.52% to 68.71%) and oxygen (5.61% to 8.13%), while slightly lowering hydrogen (3.87% to 3.56%) and nitrogen (1.43% to 1.36%), with minimal sulphur change (0.74% to 0.75%). This suggests sawdust's influence on oxygenation, echoing studies where biomass raises Oxygen relative to coal. Compared to pure coal (Sample 5), blends with sawdust addition show higher Carbon and Oxygen, indicating hybrid fuels with balanced combustion properties but potentially lower emissions than coal alone. (Umubigho et al., 2025; Maj et al., 2025).

Table 4: Ultimate Analysis Results of Biomass Coal Pellets

Ultimate Analysis	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
% Sulphur Content	0.74	0.92	0.75	1.11	0.73	0.67
% Carbon Content	57.52	71.06	68.71	76.00	46.33	50.12
% Oxygen Content	5.61	4.66	8.13	5.27	3.09	4.05
% Nitrogen Content	1.43	0.98	1.36	0.65	1.53	1.38
% Hydrogen Content	3.87	5.99	3.56	3.53	4.18	5.45

Chemical Formulation of Biomass-Coal Pellets

The equivalent chemical composition (molecular formula) by mass of each of the pellets is $C_aH_bO_cN_dS_e$ as stated in Equation 6. Thus, data on the various constituents in Table 4 (ultimate analysis results) were used to evaluate the unknown variables (a, b, c, d, and e) and determine the chemical formula of biomass-coal co-fired pellets.

The molecular masses of carbon, hydrogen, oxygen, nitrogen, and sulphur are 12, 1, 16, 14, and 32, respectively.

Therefore, the chemical composition for sample 1 is as follows:

C$arbon\ constituent$:$12a$ = 57.52, a = 4.79333

H$ydrogen\ constituent$:$1b$ = 3.87, b = 3.87

O$xygen\ constituent$:$16c$ = 5.61, c = 0.35063

N$itrogen\ constituent$:$14d$ = 1.43, d = 0.10214

S$ulphur\ constituent$:$32e$ = 0.74, e = 0.02313

From the calculation, the chemical composition for sample 1 is $C_{4.79333}H_{3.87}O_{0.35063}N_{0.10214}S_{0.02313}$

Therefore, the chemical formula for the Sample 1 co-fired optimised pellet is $C_{4.79333}H_{3.87}O_{0.35063}N_{0.10214}S_{0.02313}$. A similar method of evaluation was used for the biomass-Coal pellets of Samples 2, 3, 4, 5, and 6. The equivalent chemical compositions of all pellets are presented in Table 5.

Table 5: Chemical formula for co-fired pellets samples

S/N	Pellets Samples	Equivalent Chemical Formula
1	Sample 1	$C_{4.79333}H_{3.87}O_{0.35063}N_{0.10214}S_{0.02313}$
2	Sample 2	$C_{5.92167}H_{3.99}O_{0.29125}N_{0.07}S_{0.02875}$
3	Sample 3	$C_{5.72583}H_{3.56}O_{0.50813}N_{0.09714}S_{0.02344}$
4	Sample 4	$C_{6.3}H_{3.53}O_{0.32938}N_{0.04643}S_{0.05531}$
5	Sample 5	$C_{3.86}H_{4.16}O_{0.19313}N_{0.10929}S_{0.02281}$
6	Sample 6	$C_{4.17667}H_{5.45}O_{0.25313}N_{0.09857}S_{0.02093}$

Effect of the Optimisation Ratio on the Combustion Emissions of Co-fired Pellets

According to Onochie et al. (2024), combustion is a chemical process in which a fuel reacts with oxygen to burn and produce heat. Onochie et al. (2024) further opined that the analysis or composition of a fuel under consideration for combustion involves the concentrations of carbon, hydrogen, nitrogen, and sulphur. Similarly, Ramesh et al. (2022) and Paraschiv et al. (2019) defined combustion analysis as a significant determinant in the operation and control of combustion processes. However, Anufriev et al. (2021) stated that for combustion to be safe and effective, the correct amount and mixture of fuel and oxygen must be fed into the burner. Consequently, subsections 3.5.1 to 3.5.6 present and discuss the effect of the optimisation ratio on the combustion emissions of CO_2 and SO_2 from co-fired pellets.

Sample 1 optimised co-fired pellet on combustion CO_2 and SO_2

The stoichiometric equation for the combustion of sample 1 optimised pellets $C_{4.18167}H_{3.33}O_{0.26750}N_{0.10357}S_{0.01781}$ is given by Equation 7.

$C_aH_bO_dN_eS_f + y_5\ [O_2 + (79/21)\ N_2] \rightarrow p_5CO_2 + q_5H_2O + r_5SO_2 + [t_5 + y_5\ (79/21)\ N_2]$

Hence, balancing the constituents on both sides of the combustion equation yields the final stoichiometric combustion for sample 1, Biomass-coal pellets.

$C_{4.79333}H_{3.87}O_{0.35063}N_{0.10214}S_{0.02313}+ \ 5.6090[O_2 + 3.762N_2] \rightarrow 4.793CO_2 + 1.935H_2O + 0.02313SO_2 + 21.151N_2$

Wet and dry bases Sample 1 Pellet

The total amount of wet products is 27.9021kmol, while the total amount of dry products is 25.9671kmol. Using Equations 8 and 9, the percentage composition of wet products is as follows: 17.18% CO_2, 6.93% H_2O, 0.083% SO_2, and 75.80% N_2. On dry analysis: 18.46% CO_2, 0.089% SO_2, and 81.45% N_2. Figure 5 presents a graphical representation of biomass coal pellets based on the wet and dry percentage composition of combustion emission gases.

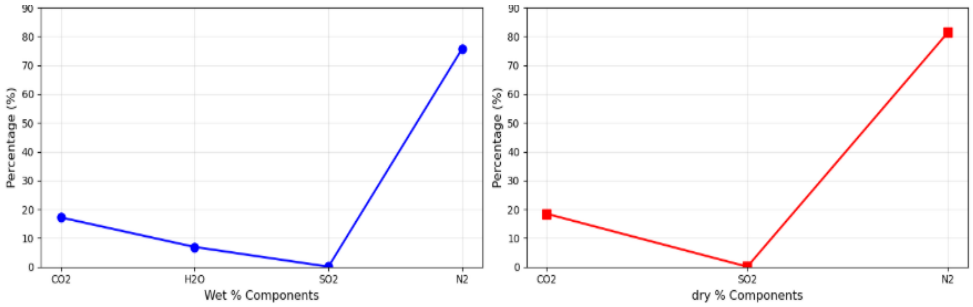


Figure 5: Wet and Dry Composition Analysis for Sample 1

From Figure 5, comparative analysis showed that the percentage composition of CO_2 and SO_2 emissions on a wet basis is lower than on a dry basis. However, both the wet and dry analyses validate Onochie et al. 2025 and the Bureau of Energy Efficiency, which suggested that SO_2 should not exceed 0.5% in the fuel due to the high corrosion rate it causes in steam boilers.

Sample 2 optimised co-fired pellet on combustion CO_2 and SO_2

The stoichiometric equation for the combustion of sample 2 optimised pellets $C_{5.92167}H_{3.99}O_{0.29125}N_{0.07}S_{0.02875}$ is given by Equation 7.

$C_aH_bO_dN_eS_f + y_1\ [O_2 + (79/21)\ N_2] \rightarrow p_1CO_2 + q_1H_2O + r_1SO_2 + [t_1 + y_1\ (79/21)\ N_2]$

Hence, balancing the constituents on both sides of the combustion equation yields the final stoichiometric combustion for the sample-2-optimised co-fired pellets.

$C_{5.92167}H_{3.99}O_{0.29125}N_{0.07}S_{0.02875}+ \ 6.802295[O_2 + 3.762N_2] \rightarrow 5.922CO_2 + 1.995H_2O + 0.02875SO_2 + 25.6252N_2$

Wet and dry bases Sample 2 pellet

The total amount of wet products is 33.5710kmol, while the total amount of dry products is 31.5760kmol. Using Equations 8 and 9, the percentage composition of wet products is as follows: 17.64% CO_2, 5.94% H_2O, 0.086% SO_2, and 76.33% N_2. On dry analysis: 18.75% CO_2, 0.086% SO_2, and 81.15% N_2. Figure 6 presents co-fired pellets with 10% sawdust, 90% Coal, and 30% Styrofoam binder, based on the wet and dry percentages of combustion emission gases.

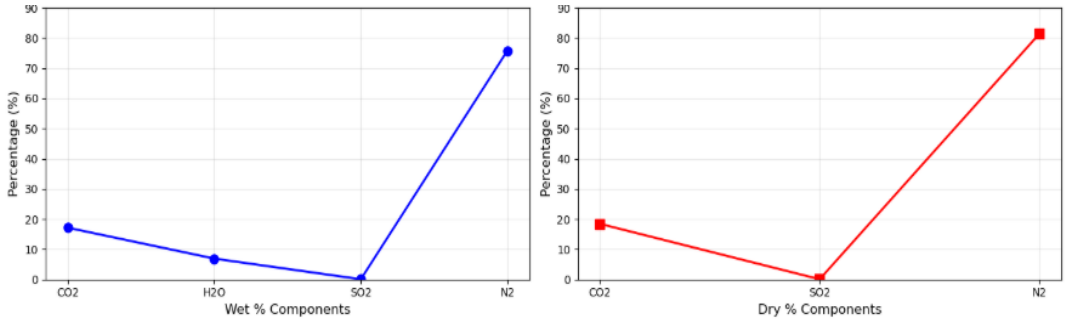


Figure 6: Wet and Dry Composition Analysis for Sample 2

From Figure 6, the comparative analysis of sample 2 with the addition of Styrofoam binder showed that the percentage composition of CO_2 and SO_2 emissions on a wet basis is lower than on a dry basis. Compared with sample 1 of the same optimum mix but without binder, adding 30% Styrofoam to the sawdust-coal pellet (Sample 2 vs Sample 1) results in cleaner flue gas, lower SO_2 levels, lower moisture levels, and slightly higher CO_2 levels. This shows that Styrofoam is a functional high-energy, low-pollutant additive for waste-derived fuels. However, both the wet and dry analyses validate Onochie et al. 2025 and the Bureau of Energy Efficiency, which suggested that SO_2 should not exceed 0.5% in the fuel due to the high corrosion rate it causes in steam boilers.

Sample 3 optimised co-fired pellet on combustion CO_2 and SO_2

The stoichiometric equation for the combustion of sample 3 optimised pellets $C_{5.72583}H_{3.56}O_{0.50813}N_{0.09714}S_{0.02344}$ is given by Equation 7.

$C_aH_bO_dN_eS_f + y_1\,[O_2 + (79/21)\,N_2] \rightarrow p_1CO_2 + q_1H_2O + r_1SO_2 + [t_1 + y_1\,(79/21)\,N_2]$

Hence, balancing the constituents on both sides of the combustion equation yields the final stoichiometric combustion for the optimised co-fired sample 3 pellets.

$C_{5.72583}H_{3.56}O_{0.50813}N_{0.09714}S_{0.02344} + 6.385[O_2 + 3.762N_2] \rightarrow 5.726CO_2 + 1.78H_2O + 0.02344SO_2 + 24.018N_2$

Wet and dry bases Sample 3 pellet

The total amount of wet products is 31.5474kmol, while the total amount of dry products is 29.7674kmol. Using Equations 8 and 9, the percentage composition of wet products is as follows: 18.15% CO_2, 5.64% H_2O, 0.074% SO_2, and 76.13% N_2. On dry analysis: 19.24% CO_2, 0.079% SO_2, and 80.69% N_2. Figure 7 presents co-fired pellets with 20% sawdust and 80% Coal, based on the wet and dry percentage composition of combustion emission gases.

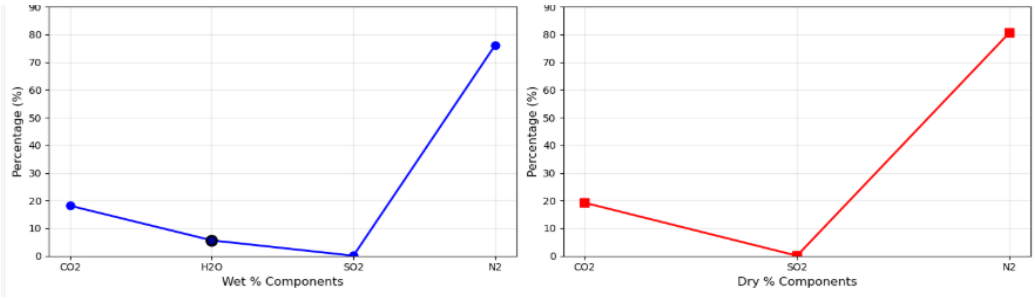


Figure 7: Wet and Dry Composition Analysis for Sample 3

From Figure 7, comparative analysis showed that the percentage composition of CO_2 and SO_2 emissions on a wet basis is lower than on a dry basis. Compared to Sample 1 (10% sawdust, 90% Coal and no Styrofoam) and Sample 2 (10% sawdust, 90% Coal and 30% Styrofoam), Sample 3 has cleaner emissions: it has higher CO_2 levels (which means it is using carbon more efficiently), much lower SO_2 levels (which is suitable for acid rain/SO_2 regulations), and less moisture. These trends support the benefits of co-firing biomass with coal, such as lower SO_2 and NOx emissions and higher combustion efficiency. This aligns with what has been written about biomass-coal blends, where adding more biomass often significantly lowers SO_2 levels by reducing sulphur in the fuel and altering how ash interacts with it (Zhakupov et al., 2022; Zhuikov et al., 2025). The profile is still good for burning waste-derived pellets efficiently without polluting too much.

Sample 4 optimised co-fired pellet on combustion CO_2 and SO_2

The stoichiometric equation for the combustion of sample 4 optimised pellets $C_{6.3}H_{3.53}O_{0.32938}N_{0.04643}S_{0.05531}$ is given by Equation 7.

$C_aH_bO_dN_eS_f + y_1\,[O_2 + (79/21)\,N_2] \rightarrow p_1CO_2 + q_1H_2O + r_1SO_2 + [t_1 + y_1\,(79/21)\,N_2]$

Hence, balancing the constituents on both sides of the combustion equation yields the final stoichiometric combustion for the optimised co-fired sample 4 pellets.

$C_{6.3}H_{3.53}O_{0.32938}N_{0.04643}S_{0.05531} + 7.073[O_2 + 3.762N_2] \rightarrow 6.3CO_2 + 1.7658H_2O + 0.05531SO_2 + 26.632N_2$

Wet and dry bases Sample 4 pellet

The total amount of wet products is 34.7531kmol, while the total amount of dry products is 32.9873kmol. Using Equations 8 and 9, the percentage composition of wet products is as follows: 18.13% CO_2, 5.03% H_2O, 0.159% SO_2, and 76.12% N_2. On dry analysis: 19.10% CO_2, 0.168% SO_2, and 80.73% N_2. Figure 8 presents co-fired pellets containing 20% sawdust, 80% Coal, and 30% Styrofoam, based on wet and dry combustion emissions.

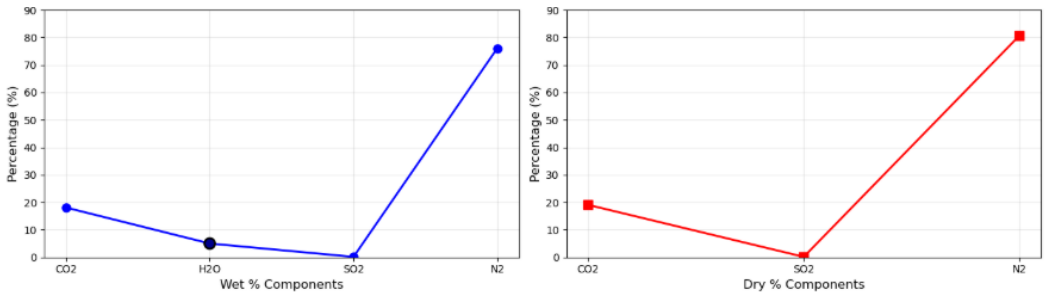


Figure 8: Wet and Dry Composition Analysis for Sample 4

Sample 4 has high combustion efficiency (high CO_2, low H_2O) and the benefits of Styrofoam-enhanced energy density, but it has higher SO_2 levels than non-plastic versions. This could mean that real-world applications need to pay more attention to emissions compliance. This is different from many studies that show that adding plastic (like polystyrene) lowers or keeps SO_2 levels low by lowering the amount of sulphur and ash that the fuel interacts with. (Bhattarai et al., 2023; Maj et al., 2025). The profile aligns with Zhakupov et al. (2022) and Zhuikov et al. (2025) regarding waste-derived pellets as viable fuels, exhibiting overall clean characteristics; however, the trends in SO_2 necessitate further investigation (e.g., ash analysis or replicate tests) to verify consistency. Both the wet and dry analyses, on the other hand, support Onochie et al. (2025) and the Bureau of Energy Efficiency, which stated that SO2 levels in fuel should not exceed 0.5% because they can cause steam boilers to corrode quickly.

Sample 5 optimised co-fired pellet on combustion CO_2 and SO_2

The stoichiometric equation for the combustion of sample 5 optimised pellets ($C_{3.86}H_{4.16}O_{0.19313}N_{0.10929}S_{0.02281}$) is given by Equation 7.

$$C_aH_bO_dN_eS_f + y_1\,[O_2 + (79/21)\,N_2] \rightarrow p_1CO_2 + q_1H_2O + r_1SO_2 + [t_1 + y_1\,(79/21)\,N_2]$$

Hence, balancing the constituents on both sides of the combustion equation yields the final stoichiometric combustion for the optimised co-fired sample 5 pellets.

$$C_{3.86}H_{4.16}O_{0.19313}N_{0.10929}S_{0.02281} + 4.826[O_2 + 3.762N_2] \rightarrow 3.86CO_2 + 2.08H_2O + 0.02281SO_2 + 18.16N_2$$

Wet and dry bases Sample 5 pellet

The total amount of wet products is 24.1228kmol, while the total amount of dry products is 22.0428kmol. Using Equations 8 and 9, the percentage composition of wet products is as follows: 16.00% CO_2, 8.62% H_2O, 0.09% SO_2, and 70.28% N_2. On dry analysis: 17.51% CO_2, 0.01% SO_2, and 83.39% N_2. Figure 9 presents co-fired pellets with 100% Coal, based on the wet and dry percentage composition of combustion emission gases.

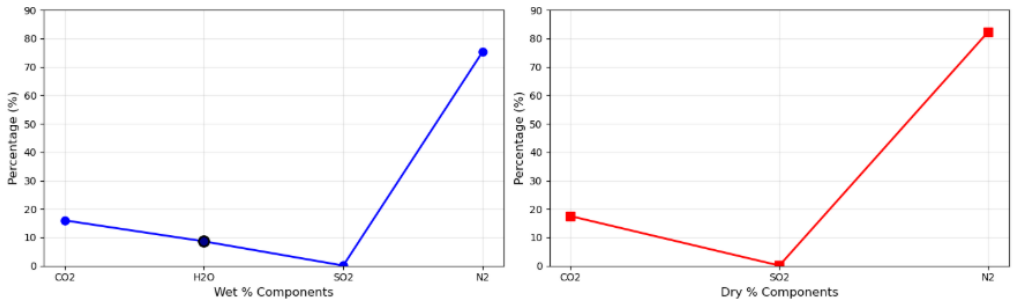


Figure 9: Wet and Dry Composition Analysis for Sample 5

Sample 5 has the same coal-burning properties and aligns with the complete oxidation of fixed carbon in a medium-rank coal (Tumuluru *et al.*, 2016). It is efficient but has more moisture and less SO_2 than blends. Adding biomass (Samples 1 and 3) usually raises CO_2 (better carbon use and more volatiles) and lowers SO_2 (dilution and ash retention). Styrofoam (Samples 2, 4, and 6) can also lower H_2O and raise CO_2 from high C input. Pure coal exhibits the "baseline" profile, characterised by elevated H_2O levels and potential increases in SO_2 exposure, without the advantages of biomass. This underscores the benefits of co-firing for emission reduction in waste-derived pellets (Thabit et al., 2022; Lizica et al., 2020).

Sample 6 optimised co-fired pellet on combustion CO_2 and SO_2

The stoichiometric equation for the combustion of sample 6 optimised pellets $C_{4.17667}H_{5.45}O_{0.25313}N_{0.09857}S_{0.02093}$ is given by Equation 7.

$C_aH_bO_dN_eS_f + y_1\,[O_2 + (79/21)\,N_2] \rightarrow p_1CO_2 + q_1H_2O + r_1SO_2 + [t_1 + y_1\,(79/21)\,N_2]$

Hence, balancing the constituents on both sides of the combustion equation yields the final stoichiometric combustion for the optimised co-fired sample 6 pellets.

$C_{4.17667}H_{5.45}O_{0.25313}N_{0.09857}S_{0.02093} + 5.434[O_2 + 3.762N_2]$

$\rightarrow 4.177CO_2 + 2.725H_2O + 0.020935SO_2 + 20.430N_2$

Wet and dry bases Sample 6 pellet

The total amount of wet products is 27.3529kmol, while the total amount of dry products is 24.6279kmol. Using Equations 8 and 9, the percentage composition of wet products is as follows: 15.27% CO_2, 9.96% H_2O, 0.08% SO_2, and 73.95% N_2. On dry analysis: 16.96% CO_2, 0.09% SO_2, and 82.95% N_2. Figure 10 presents co-fired pellets with 100% Coal and 30% Styrofoam, based on the wet and dry percentages of combustion emission gases.

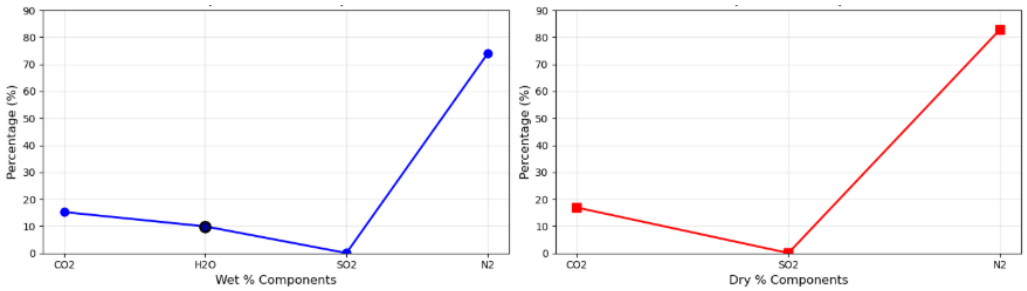


Figure 10: Wet and Dry Composition Analysis for Sample 6

Sample 6 has a high CO_2 level compared to typical coal firing and a low SO_2 level. This is because Styrofoam adds energy, but it also has more moisture and a slightly lower CO_2 level than biomass blends. Adding Styrofoam to pure coal (Sample 5) lowers SO_2 slightly (dilution benefit) but raises H_2O because more Hydrogen is added. Biomass blends (Samples 1–4) generally produce more CO_2 and less SO_2/H_2O, which shows that co-firing is better for emissions. The profile supports the use of waste-derived pellets as low-pollutant fuels. Styrofoam helps coal-dominant systems perform better with SO_2, which aligns with studies on plastic-coal co-combustion showing that low Sulphur additives can reduce emissions while maintaining efficiency (Bhattarai et al., 2023; Zhuikov et al., 2025).

Comparative Analysis of Wet and Dry % CO_2 emissions of Samples

Figure 11 displays the graphical wet and dry percentage composition of flue gas emissions for samples 1-6. It was observed that CO_2 levels in the flue gas vary with pellet composition. For example, biomass-inclusive blends (Samples 1–4) usually have higher levels (wet: 17.18–18.15%; dry: 18.46–19.24%) than pure coal (Sample 5: wet 16.00%, dry 17.51%) and coal-Styrofoam (Sample 6: wet 15.27%, dry 16.96%). This implies improved carbon oxidation or diminished excess air dilution in mixtures containing sawdust, consistent with co-combustion research indicating that biomass incorporation (e.g., 10–30 wt.%) can increase CO_2 levels due to enhanced volatile release and synergistic effects. The normal amount of CO_2 in coal flue gas is 12–15 mol-% (volume %), but the higher amounts here (15–19%) may be due to test-specific conditions, such as less extra air, as shown by the Nitrogen levels, which were about 75–76% wet across samples. (Zhuikov 2025 et al.; Songolzadeh et al. 2014) Adding Styrofoam has mixed effects: it slightly raises CO_2 levels in sawdust blends (Sample 2 vs 1: wet +0.46%; Sample 4 vs 3: wet -0.02%, which is not much) but lowers CO_2 levels in pure coal (Sample 6 vs 5: wet -0.73%). This could mean that polystyrene's high carbon content (about 92%) is affecting things in different ways, possibly because of the higher H_2O content (9.96% in Sample 6) or because of changes in the way plastic and coal mix together, like in tri-fuel (coal-biomass-polyethylene) combustion, where plastics affect the release of volatile substances but may not always increase the amount of CO_2. (Yaqub et al., 2020; Xinjie et al., 2021). Increasing sawdust from 10% (Sample 1) to 20% (Sample 3) increases CO_2 (wet +0.97%), consistent with the idea that more organics in biomass lead to more complete combustion.

This pattern is also actual for Styrofoam, but only slightly (Sample 2 vs 4: wet +0.49%). In general, blends are better at using CO_2 (more output per fuel) than pure coal. This enables waste valorisation, thereby lowering GHG intensity in co-firing situations. (Chowdhury et al., 2019).

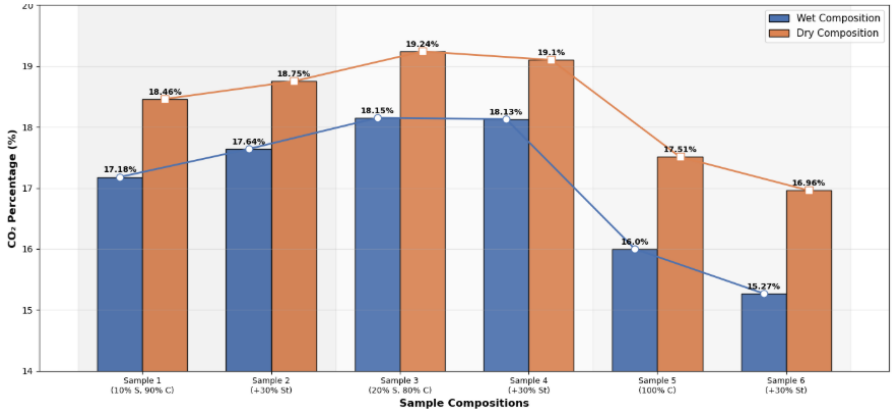


Figure 11: Wet and Dry Composition Analysis of % CO_2 emissions of samples

Comparative Analysis of Wet and Dry % SO_2 Emissions of Samples

The SO_2 levels in the flue gas samples are always low (wet: 0.074–0.159%; dry: 0.01–0.168%). This aligns with the Bureau of Energy Efficiency's guidance, which states that SO2 should not exceed 0.5%. This is also in line with the low sulphur content of the base fuels (ultimate analysis: 0.67–1.11% Sulphur), which is typical of low-to-medium sulphur coals and additives such as biomass (sawdust: 0.1–0.5% Sulphur) and polystyrene (Styrofoam: 0% Sulphur). These levels are much lower than usual for burning coal (0.2–1% SO_2 in flue gas for high-sulphur coals), making them suitable for applications with strict emissions controls. (Rokni et al., 2018). Adding Styrofoam has different effects. For example, it makes sawdust blends slightly stronger (Sample 2 vs 1: wet +0.003%; Sample 4 vs 3: wet +0.085%, a sharp rise that could be due to changes in how the ash interacts or differences in the test), but it makes pure coal weaker (Sample 6 vs 5: wet -0.01%). This mixed trend is similar to studies on co-combustion, which show that synthetic plastics such as polyethene or tyres can reduce SO_2 emissions by lowering the fuel's sulphur content. However, the effects can be different. For example, co-firing refuse-derived fuel (RDF, including plastics) with coal reduced SO_2 from 387 ppm to 50 ppm at a 25/75 coal/RDF ratio. In another instance, the amalgamation of waste tyres and plastics with biomass reduced SO_2 levels compared to coal alone, due to dilution and a lower overall sulphur input. (Isaac and Bada, 2022; Carmo-Calado et al., 2020). Increasing the amount of sawdust (Sample 3 vs 1: wet -0.009%) lowers SO_2, in line with biomass dilution and alkaline ash's capture of sulphur through sulfation reactions, which often lowers emissions in proportion to the amount of biomass. This is true for Styrofoam in lower-sawdust blends (Sample 2 vs 1). However, it reverses in higher-sawdust blends (Sample 4 vs 2: wet +0.073%), suggesting that 20% sawdust in addition to Styrofoam could have adverse

effects, such as reducing ash reactivity. The literature substantiates that biomass-coal co-firing generally reduces SO_2 emissions by 10–50% with 15–25% woody biomass, demonstrating synergies that extend beyond mere dilution, as alkali metals form sulfates. (Roy et al., 2024; Jurado et al., 2017). All blends except Sample 4 have lower or similar SO_2 levels than pure coal (Sample 5). This shows that co-firing can help reduce emissions. In general, both the wet and dry analyses of these pellets support the findings of Onochie et al. (2025) and the Bureau of Energy Efficiency, which stated that SO2 levels in fuel should not exceed 0.5% because they can cause steam boilers to corrode quickly. These results suggest that the samples could lead to cleaner combustion in waste-to-energy systems, with biomass/Styrofoam being the best way to control SO_2 levels. However, Sample 4's outlier needs more investigation to ensure that it works consistently.

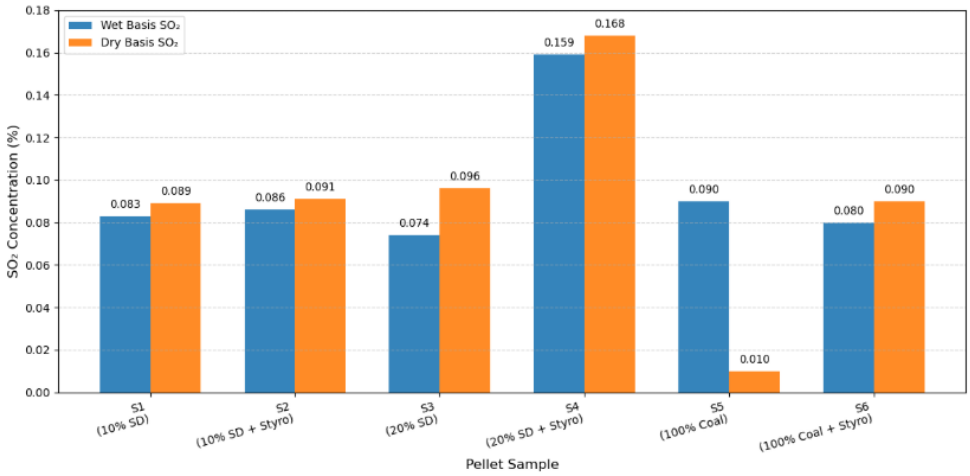


Figure 12: Wet and Dry Composition Analysis of % SO_2 emissions of samples

Conclusion

This study demonstrates that Styrofoam serves effectively as an energy-dense binder that acts as a dilution or concentration effect depending on the baseline biomass-coal mixing matrix in sawdust-coal pellets, enhancing energy content by 8.3–20.2% and reducing moisture through its hydrophobic nature. The highest energy value (22.72 MJ/kg) was obtained with 100% coal and 30% Styrofoam. Emission analysis shows that co-firing biomass and coal (Sample 3: 20% sawdust, 80% coal) yields the cleanest profile, with high CO_2 efficiency and low SO_2 (0.074% on a wet basis). Styrofoam's impact on SO_2 emissions varies by fuel type, increasing emissions in sawdust blends but reducing them in pure coal, indicating complex fuel interactions. All pellet formulations meet safety standards with SO_2 below the 0.5% corrosion threshold. Further investigation is recommended for Sample 4 due to its elevated SO_2 levels. Overall, co-densifying sawdust and Styrofoam with coal offers a sustainable waste-to-energy solution with optimized fuel quality and manageable emissions.

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