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Palm Kernel Shell and Coconut Shell Pellets Cofiring: Effect of Optimization Ratio on the Combustion Emission CO_2 and SO_2

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Abstract

Biomass is considered one of the best options for mitigating greenhouse gas (GHG) emissions and substitutes for fossil fuels. This study investigated the effect of optimization ratios on the combustion emissions of co-fired pellets produced from coconut shell (CS) and palm kernel shell (PKS) using waste paper as a binding agent. Ten pellets were produced mechanically using a manual screw press machine. Two optimization models were adopted: Model I includes ratios of 90%C:10%P, 80%C:20%P, 70%C:30%P, 60%C:40%P, and 50%C:50%P, while Model II includes ratios of 90%P:10%C, 80%P:20%C, 70%P:30%C, 60%P:40%C and 50%P:50%C . The optimized pellets were characterized through proximate and ultimate analyses in accordance with ASTM standards. Data obtained was used to analyse the combustion emissions. Results obtained revealed that, on both wet and dry bases, the 50%:50% optimization ratio in Models I and II had better potential for mitigating combustion CO_2 and SO_2 emissions than other optimization ratios, which exhibited relatively higher values. Similarly, models demonstrated more favourable emissions on a wet basis than on dry basis. Comparatively, Model I showed greater potential in CO_2 mitigation, while Model II was more effective in SO_2 mitigation. All optimized pellets in both models exhibited low CO_2 and SO_2 emissions on wet and dry composition analyses, as recommended by the Bureau of Energy Efficiency. The findings from this study underscore the potential of varying CS and PKS ratios in optimizing combustion emissions in a Biomass Power Plant, highlighting the effectiveness of CS in SO_2 reduction and PKS in CO_2 reduction.

1. Introduction

Over the past few decades, there has been rapid and sustained growth in interest on biomass fuel for energy production and utilization worldwide. From an environmental viewpoint, Casaca [1] highlighted several advantages of biomass fuels compared to conventional fossil fuels. Biomass fuels, despite their renewable nature, are lower in sulphur content and are usually CO_2 neutral. In fact, countries around the world and the European Union (EU) have intensified the use of biomass energy in the last few decades [2]. According to Hamelinck et al. [3], about 13% of the world's energy supply comes from biomass, even though fossil fuels have dominated with approximately 80% of the total for decades [4-5]. Similarly, Demirbas et al. [6] reported that about 12% of the total energy supply in industrialized countries is from biomass, while in developing countries, biomass accounts for 35% of the total energy demand. Many researchers regard biomass as one of the best options for mitigating greenhouse gas (GHG) emissions and substituting fossil fuels because it is the broadest field in renewable energy [8-9]. Tissari et al. [10] and Yin et al. [11] opined that there is no net increase in CO_2 emissions during the combustion of biomass; rather, it is a major conversion method for bio-energy. However, Zhang et al. [12] noted that biomass combustion is associated with emissions influenced not only by fuel properties but also by combustion operating parameters such as excess air ratio, mixing quality, residence time, and combustion temperature [13].

The study on the co-firing of palm kernel shell and coconut shell holds significant importance within the context of sustainable energy production and environmental impact reduction. Palm kernel shell and coconut shell are abundant biomass resources, particularly in regions with thriving palm oil and coconut industries, such as West Africa, Malaysia, and Indonesia [14]. Utilizing these agricultural residues for energy generation can help reduce dependence on non-renewable resources, aligning with global efforts to transition towards cleaner and more sustainable energy sources. Understanding the optimization ratio in the co-firing process is crucial for maximizing energy production efficiency while minimizing environmental pollutants. Sulphur dioxide (SO_2), a widely recognized air pollutant, significantly impacts ecosystems, human health, and climate [15]. Investigating the optimal ratio of palm kernel shell to coconut shell allows for a targeted approach to balance combustion characteristics, potentially mitigating the environmental impact associated with conventional combustion practices. Furthermore, this research addresses the need for alternative energy sources that contribute to energy security and meet stringent environmental standards. By examining the effect of optimization ratios on CO_2 and SO_2 emissions, this study aims to provide insights into designing biomass co-firing systems that are both economically viable and environmentally friendly. This is particularly relevant given the increasing global concern about climate change and the imperative to transition to cleaner energy solutions. The findings from this study will have practical implications for industries involved in energy production. The optimization ratio determined through this research could serve as a valuable guideline for companies seeking to adopt or improve their biomass co-firing practices. This aligns with the broader goal of fostering sustainability in the industrial sector by encouraging the adoption of environmentally responsible energy production methods.

Essentially, this study focuses on the synergistic combustion of palm kernel shell (PKS) and coconut shell pellets, aiming to unravel the intricate effects of optimizing their ratio in the context of CO_2 and SO_2 emissions during combustion. As the global community grapples with the urgent need to reduce carbon footprints and mitigate environmental impacts, understanding the nuanced dynamics of biomass co-firing becomes crucial for shaping cleaner and more efficient energy practices. This investigation delves into the complexities of balancing PKS and coconut shell pellets to achieve an optimal ratio, shedding light on the consequential implications for combustion emissions, with particular emphasis on carbon dioxide (CO_2) and sulphur dioxide (SO_2). However, it is worthy of note to state that several studies have already investigated biomass co-firing, pellet optimization, and emissions analysis. Nevertheless, none has conducted investigations on the optimization of blended CS and PKS biomass, with blended waste paper as binder, to establish the consequential implications for combustion emissions, particularly carbon dioxide (CO_2) and sulphur dioxide (SO_2). Consequently, through a comprehensive exploration of this interplay, this study aspires to investigate the consequential effects of blended CS and PKS biomass, with blended waste paper as binder on the combustion emission CO_2 and SO_2, and provide valuable insights to the burgeoning field of sustainable energy production, paving the way for informed decisions that align with environmental stewardship and energy security. Furthermore, the study will also provide insights on the optimal fuel mixture for CS and PKS biomass thereby achieving the desired reduction in combustion CO_2 and SO_2 emissions in established Biomass-Power Plants.

2. Methodology

2.1 Biomass Collection

Biomass samples, including coconut shell (CS) and palm kernel shell (PKS), were collected from selected dumpsites located at the Nigeria Institute for Oil Palm Research (NIFOR) in Edo State, Nigeria. The samples were sun-dried for a week to reduce moisture content and facilitate grinding.

2.2Pulverization, Optimization and Production of Pellets

A grinding machine was used to pulverize the samples. The optimization ratios adopted for pellet production in this study were based on the reports of Wang et al. [15], Onochie et al. [16], Khalidah et al. [17], Rohan [18], Baster [19], and Vamvuka et al. [20]. Two models for optimization are presented in Table 1.

Table 1: Optimization Models

Models	Optimization Ratio				
I	90C%:10%P	80%C:20%P	70C:30%P	60%C:40%P	50%C:50%P
II	90%P:10%C	80%P:20%C	70%P:3C	60%P:40%C	50%P:50%C

P: PKS, C: CS.

Pellets were produced manually using the optimization models with the aid of a mechanical screw press. Organic waste material, such as waste paper, was used as a binder. The pellets were then sun-dried for a week to naturally reduce moisture content and increase hardness before undergoing characterization analysis.

2.3 Characterization of Pellet Samples

2.3.1 Determination of the proximate analysis of the optimized co-fired pellets

The ASTM standard D5373-02 (2003) was used for the proximate analysis, which includes determining the physical properties of the fuel pellets. These properties consist of moisture content, ash content, volatile matter, and fixed carbon.

2.3.1.1 Moisture Content (% MC)

Each 10g sample was measured and placed separately in a porcelain container. The containers and their contents were then oven-dried at 110°C for 3 hours to achieve a constant weight. The moisture content was evaluated using Equation 1.

$$\%\ \mathrm{MC} = \frac{(\mathrm{g}-\chi)}{\mathrm{g}} \times 100 \quad (1)$$

Where g represents the weight of the sample, x is the weight of the dry matter, and (g-x) represents the weight loss.

2.3.1.2 Ash Content (% AC)

The ash content of the fuel pellets was determined using a muffle furnace. The results were evaluated using Equation 2.

$$\%\ \mathrm{Ash} = \left(\frac{\mathrm{x}}{\mathrm{g}}\right) \times 100 \quad (2)$$

Where, g denotes the weight of the sample, and x is the weight of ash

2.3.1.3 Volatile Matter (% VM)

The volatile matter of the fuel pellets was evaluated using Equation 3.

$$\%\ \mathrm{V.M} = \frac{\mathrm{x-\ y}}{\mathrm{g}} \times 100 \quad (3)$$

Where, g denotes the weight of the sample, x the weight of dry matter, and y the weight of the residues.

2.3.1.4 Fixed Carbon (% FC)

The fixed carbon is evaluated using Equation (4), which is the difference between 100% and the summation of other properties.

$$\%FC = 100 - (VM + MC + Ash) \quad (4)$$

Where VM denotes volatile matter, MC denotes moisture content, and Ash denotes ash content.

2.3.2 Determination of the Ultimate Analysis of the Optimized Co-fired Pellets

The ultimate analysis indicates the chemical composition of the optimized pellets and includes percentage content of constituents such as carbon, hydrogen, sulphur, nitrogen and oxygen.

2.3.2.1 Carbon content (%CC)

The carbon content was analyzed using equation 5.

$$\%\ \mathrm{Carbon} = \frac{(\mathrm{B-T}) \times \mathrm{M} \times 0.003 \times 100 \times 1.33}{\mathrm{g}} \quad (5)$$

Where, B = Blank Titre, T = Sample Titre and g = Weight of sample

2.3.2.2 Nitrogen content (%NC)

The nitrogen content was analyzed using equation 6.

$$\%\ \mathrm{Nitrogen} = \frac{(\mathrm{T} \times \mathrm{M} \times 0.014 \times \mathrm{DF})}{\mathrm{g}} \times 100 \quad (6)$$

Where, M = molarity of the acid used, g = Weight of sample, T = Titre value and DF = Dilution factor

2.3.2.3 Sulphur content (% SC)
The sulphur content was analyzed using equation 7.

$$\% \text{ Sulphur} = \frac{\chi \times 0.1373}{g} \times 100 \quad (7)$$

where, g = weight of sample and x = weight of $BaSO_4$

2.3.2.4 Hydrogen content (%HC)
The hydrogen content was analyzed using equation 8.

$$\% \text{ Hydrogen} = \frac{\text{wt of } H_2O \times 0.1119 \times 100}{\text{wt of pellet}} \quad (8)$$

where 0.1119 is a constant derived from empirical equation in Leibig-Pregle method

2.3.2.5 Oxygen content (%OC)
The oxygen content was analyzed using equation 9.

$$\%Oxygen = 100 - (C + H + N + S + \%Ash) \quad (9)$$

2.4 Analysis of the Calorific Value of the Optimized Co-fired Pellets

Using the data from the laboratory analysis, Equation 10 was used to calculate the calorific value (CV) (kJ/kg). The volatile matter, moisture, and ash were considered as the key variables (inputs) for determining the calorific value [21]. The calorific value based on ultimate (elemental) analysis considers the contents of C, H, N, S, and O elements [22].

$$\text{CV} = \frac{\text{E}\Delta\text{T} - \Phi - \text{V}}{\text{g}} \quad (10)$$

where E is energy equivalent of the calorimeter (13,039.308 kJ/^{o}C), ΔTis change in temperature (^{o}C), Φ is 2.3 time length of burnt wire (kJ), g is mass of sample (kg), and V is volume of alkali in calorimeter (kJ).

2.5 Combustion Emissions and Performance Analysis

To determine the combustion performance and emissions (CO_2 and SO_2) of the fuel pellets, it is necessary to evaluate the chemical formula of each co-fired optimized pellet. Therefore, data from the ultimate analysis, which includes carbon, hydrogen, oxygen, nitrogen, and sulfur, will be used. The equivalent chemical formula is expressed as $C_aH_bO_cN_dS_e$.The combustion performance analysis is determined using Equation 11.

$$C_aH_bO_cN_dS_e + xO_2 + x\left({}^{79}\!/_{21}\right)N_2 \rightarrow pCO_2 + qH_2O + rSO_2 + sN_2 \quad (11)$$

Equation 12 is used to determine the percentage composition of combustion product gases.

$$\%\,Composition\ of\ component = \frac{\text{Amount of substance of component}}{\text{Total amount of substance of all components}} \quad (12)$$

3. Results And Discussion

3.1 Effect of the Optimization Ratio on the Calorific Value of Co-fired Pellets

From Equation 10, data obtained were used to calculate the calorific values of the optimized pellets for Model I and Model II and presented in Figures 1a and 1b.

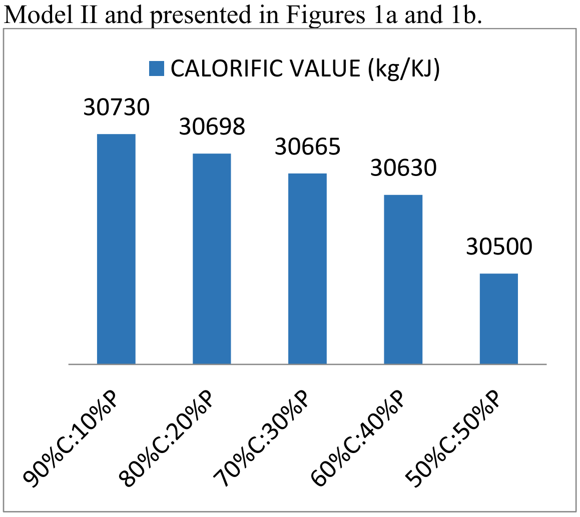

Figure 1a: Optimized pellets (Model I)

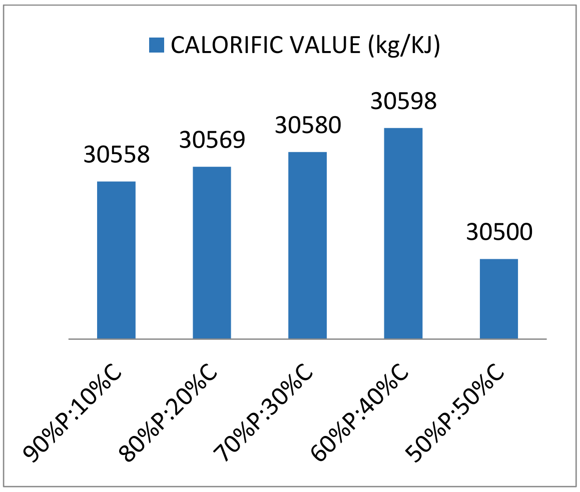

Figure 1b: Optimized pellets (Model II)

As presented in Figure 1a (Model I), it was observed that as the percentage ratio of the coconut shell (C) decreases, the calorific value of all optimized pellets declined (i.e. value shifted from left to right) from 90%C:10%P to 50%C:50%P. On the other hand, as the percentage ratio of the palm kernel shell (P) increases, calorific value increases (i.e. value shifted from right to left). In Figure 1b (Model II) however, similar scenario played out but in opposite manner. That is, as the percentage ratio of the coconut shell (C) increases, the calorific value of the all optimized pellets continue to increase from 90%C:10%P to 60%P:40%C optimized pellets (i.e. shifted from right to left). Meanwhile, as the percentage ratio of the palm kernel shell (P) decreases, the calorific value increases (i.e. shifted from left to right).
Essentially, findings here revealed that increase in the percentage constituent of coconut shell (C) increases the calorific values of all the optimized pellets, while a decrease in the percentage constituent of palm kernel shell decreases the CV of optimized pellets. This validates the fact that coconut shell has a higher CV than palm kernel shell. In Model I, the CV ranged from 30, 630 kJ/kg to 30, 730 kJ/kg, while the optimal ratio with the highest CV is 90%C:10%P and the lowest is 60%C:40%P. Meanwhile, in Model II, the CV ranged from 30, 558 kJ/kg to 30, 598 kJ/kg while the optimal ratio with the highest CV is 60%P:40%C. The calorific value for 50%C:50%P and 50%P:50%C remained the same in Models I and II because of the equality between the individual constituents of the cofired pellets.
It is worthy of note that for industrial consideration and application of cofired pellets (i.e. coconut and palm kernel shells), the optimal mixing ratio for the production of pellets is 90%C:10%P which also validates the value of the percentage carbon in the ultimate analysis (Table 3a). Similarly, the optimal mixing ratio 90%C:10%P as well as all the cofired pellets, validates the percentage volatile matter (VM) in the proximate analysis (Tables 2a & 2b). The high VM shows that the ignition of the cofired fuels will certainly produce combustion performance that is most likely going to be efficient and effective.

3.1 Effect of the Optimization Ratio on the Proximate Analysis of the Co-fired Pellets

Tables 2a and 2b present the results of the proximate analysis of the optimized co-fired pellets for Model I and Model II, respectively.

Table 2a: Proximate analysis of optimized co-fired pellets (Model I)

Parameter	Optimization Ratio						
	100%P	100%C	90%C: 10%P	80%C: 20%P	70%C: 30%P	60%C: 40%P	50%C: 50%P
% MC	9.00	10.23	8.98	8.96	8.70	8.58	9.60
% VM	88.61	86.11	87.95	88.11	88.53	88.79	87.30
% AC	1.40	2.24	1.68	1.59	1.48	1.41	1.83
% FC	0.99	1.42	1.39	1.34	1.29	1.22	1.27

Table 2b: Proximate analysis of optimized co-fired pellets (Model II)

Parameter	Optimization Ratio			
	90%P:10%C	80%P:20%C	70%P:30%C	60%P:40%C
% MC	9.37	9.33	9.27	9.22
% VM	87.91	87.83	88.06	88.36
% AC	1.59	1.53	1.49	1.43
% FC	1.13	1.08	1.02	1.00

As revealed from Tables 2a and 2b, the percentage moisture content (%MC) of all optimized co-fired pellets was found to be within the range of 10-15%, which implies that these pellets are suitable for efficient combustion [23]. In Model I, as shown in Table 2a, the ratio of PKS increases as CS decreases in the co-fired pellets. Consequently, the %MC decreases because 100% PKS (i.e., 100% P) has a lower %MC than 100% CS (i.e., 100% C). Similarly, in Model II (Table 2b), as the ratio of PKS decreases and CS increases in the mixture, there is a corresponding shift in the %MC of the co-fired pellets. The co-fired pellets with the best optimal ratio, with respect to %MC, is the 60%C:40%P co-fired pellets (Model I) with 8.58% MC.

Maciejewska et al. [24] reported that low %MC in biomass aids in storage and prevents decomposition and rotting. According to Kakooza [25], fuel pellets with higher volatile matter (%VM) ignite easily and have enhanced combustion performance due to increased chemical activity. Oyelaran et al. [26] also reported that biomass fuels with high %VM ignite and burn easily, though they produce long smoky flames. Again, regarding %VM, the optimal ratio is the 60%C:40%P co-fired pellets (Model I) with 88.79% VM.

In terms of percentage ash content (%AC), the 60%C:40%P co-fired pellets (Optimization Model 1) are preferred, with 1.41% AC. Higher %AC indicates more mineral matter in the fuel, which is undesirable as it reduces handling and burning capacity and affects combustion efficiency [27]. Similarly, studies by Loo and Koppejan [28], Japhet et al. [29], and Onochie et al. [30] also reported that higher %AC affects the calorific value (CV) of a fuel. The %AC results revealed that all co-fired pellets exhibited low ash content, ranging from 1.41% to 1.83%, which is significantly lower than the Bureau of Energy Efficiency's recommended ash level of 5 to 40% for boilers. Overall, the results of the proximate analysis validate the findings of several researchers [23 - 30].

3.2 Effect of the Optimization Ratio on the Ultimate Analysis of the Co-fired Pellets

Tables 3a and 3b present the result of the ultimate analysis of the co-fired pellets for Model I and Model II respectively.

Table 3a: Ultimate analysis of optimized co-fired pellets (Model I)

Parameter	Optimization Ratio						
	100%C	100%P	90%C: 10%P	80%C: 20%P	70%C: 30%P	60%C: 40%P	50%C: 50%P
% CC	62.4	46.28	60.0	57.6	55.2	53.8	51.4
% NC	0.10	0.90	0.14	0.16	0.20	0.23	0.25
% SC	0.42	0.10	0.39	0.35	0.33	0.30	0.26
% HC	5.67	5.59	5.54	5.49	5.43	5.38	5.34
% OC	30.01	46.44	32.34	34.81	37.36	38.88	40.92

Table 3b: Ultimate analysis of optimized co-fired pellets (Model II)

Parameter	Optimization Ratio			
	40%C:60%P	30%C:70%P	20%C:80%P	10%C:90% P
% CC	48.1	45.2	43.6	40.9
% NC	0.27	0.29	0.32	0.34
% SC	0.22	0.20	0.18	0.14
% HC	5.30	5.24	5.18	5.13
% OC	44.65	47.58	49.23	51.90

In Table 3a, the percentage carbon content (%CC) of the optimized pellets range from 40.9% to 60.0%. This validates the report of Mitchual et al. [31] and Gil et al. [32] which suggests that %CC should be within the range of 44% to 52%.The percentage sulphur content (%SC) of the optimized pellets range between 0.14% and 0.39% which validates the work of Onochie et al [33] which states that high %SC causes corrosion due to the rate of sulphuric acid formed during and after combustion of fuel. The %SC also validates the work of Olatunde et al [34] which reported % SC ≤ 0.08%. The percentage nitrogen content (%NC) of the optimized pellets ranges between 0.14% and 0.34%. This is similar with the values obtained as standard limits in [34].

3.3 Effect of Optimization Ratio on the Chemical Formula of 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 11. Thus, data containing the various constituents in Table 3 (ultimate analysis results) was used to evaluate the unknown variable (a, b, c, d, and e) so as to determine the chemical formula of optimized co-fired pellets.

3.3.1.1 Chemical formula of 90%C: 10%P

The molecular masses of carbon, hydrogen, oxygen, nitrogen, and sulphur are 12, 1, 16, 14, and 32, respectively. Therefore, the chemical composition is as follows:

$Carbon\ constituent: 12a = 60.0, \quad a = 5$

$Hydrogen\ constituent: 1b = 5.54, \quad b = 5.54$

$Oxygen\ constituent: 16c = 32.34, \quad c = 2.0213$

$Nitrogen\ constituent: 14d = 0.14, \quad d = 0.01$

$Sulphur\ constituent: 32e = 0.39, \quad e = 0.01393$

Therefore, the chemical formula for the 90%C:10%P co-fired optimized pellet is $C_5H_{5.54}O_{2.0213}N_{0.01}S_{0.01393}$. A similar method of evaluation was used for 80%C:20%P, 70%C:30%P, 60%C:40%P, 50%C:50%P, 90%P:10%C, 80%P:20%C, 70%P:30%C, and 60%P:40%C co-fired optimized pellets. The equivalent chemical compositions of all pellets are presented in Table 4.

Table 4: Chemical formula for optimized pellets

S/N	Co-fired optimized pellets	Equivalent chemical formula
1.	90%C:10%P	$C_5 H_{5.54} O_{2.0213} N_{0.01} S_{0.01393}$
2.	80%C:20%P	$C_{4.8}H_{5.49}O_{2.18} N_{0.0114}S_{0.0109}$
3.	70%C:30%P	$C_{4.6} H_{5.43} O_{2.34} N_{0.0149} S_{0.0103}$
4.	60%C:40%P	$C_{4.48} H_{5.38} O_{2.43}N_{0.0164} S_{0.0194}$
5.	50%C:50%P	$C_{4.28} H_{5.34} O_{2.56}N_{0.0179} S_{0.0081}$
6.	90%P:10%C	$C_{3.41} H_{5.13} O_{3.24}N_{0.0243} S_{0.0044}$
7.	80%P:20%C	$C_{3.63} H_{5.18} O_{3.08} N_{0.0229} S_{0.0056}$
8.	70%P:30%C	$C_{3.77} H_{5.24} O_{2.97}N_{0.0207} S_{0.0063}$
9.	60%P:40%C	$C_{4.01} H_{5.30} O_{2.79}N_{0.0193} S_{0.0069}$

3.4 Effect of the Optimization Ratio on the Combustion Emissions of Co-fired Pellets

According to Lizica et al. [35], the combustion of a fuel can be defined as a chemical process in which the fuel reacts with oxygen to burn and produce heat. Lizica et al. further opined that the analysis or composition of a fuel being considered for combustion deals with the concentrations of carbon, hydrogen, nitrogen, and sulfur. Similarly, Ramesh et al. [36] defined combustion analysis as a major determinant in the operation and control of combustion processes. However, Anufriev et al. [37] stated that for combustion to be safe and effective, the right quantity and mixture of fuel and oxygen must be fed into the burner. Consequently, sub-sections 3.4.1 to 3.4.9 presents and discusses the effect of the optimization ratio on the combustion emission CO_2 and SO_2 of co-fired pellets

3.4.1 Effect of 90%C: 10%P optimized co-fired pellet on combustion CO_2 and SO_2

The stoichiometric equation for the combustion of 90%C: 10%P optimized pellets [$C_5H_{5.54}O_{2.0213}N_{0.01}S_{0.01393}$] is given by Equation 13.

$$C_5H_{5.54}O_{2.0213}N_{0.01}S_{0.01393} + y_1[O_2 + (^{79}/_{21})N_2] \rightarrow p_1CO_2 + q_1H_2O + r_1SO_2 + [t_1 + y_1(^{79}/_{21})N_2] \quad (13)$$

Hence, balancing the constituents on both sides of the combustion equation yields the final stoichiometric combustion for the 90%C:10%P optimized co-fired pellets.

$$C_5H_{5.54}O_{2.0213}N_{0.01}S_{0.01393} + 5[O_2 + (^{79}/_{21})N_2] \rightarrow 5CO_2 + 2.77H_2O + 0.01393SO_2 + 18.81N_2 \quad (14)$$

3.4.1.1 Wet and dry bases analyses of 90%C:10%P optimized co-fired pellet

Therefore, from Equation 14, the total amount of wet products is 26.594 kmol, while the total amount of dry products is 23.82393 kmol. Using Equation 12, the percentage composition of wet products is as follows: 18.80% CO_2, 10.4159% H_2O, 0.0524% SO_2, and 70.73% N_2. On dry analysis: 20.99% CO_2, 0.058% SO_2, and 78.95% N_2. Figures 1a and 1b present the 90%C:10%P co-fired pellets based on the wet and dry percentage composition of combustion emission gases.

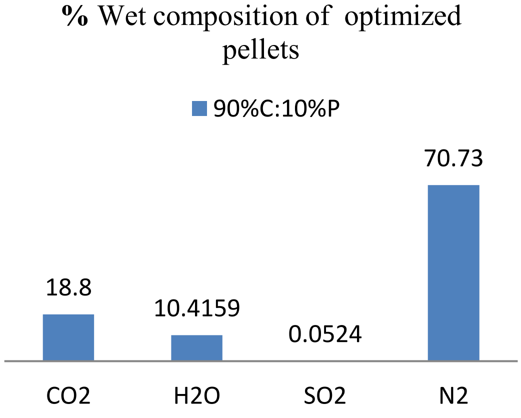

Figure 2a: Wet composition analysis

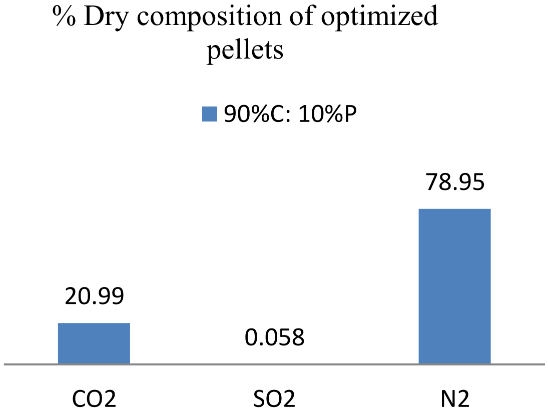

Figure 2b: Dry composition analysis

From Figures 2a and 2b, 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 Olatunde et al. [34] and the Bureau of Energy Efficiency, which suggested that SO_2 should not be above 0.5% in fuel due to the high corrosion rate it causes in steam boilers.

3.4.2 Effect of 80%C: 20%P optimized co-fired pellet on combustion CO_2 and SO_2

The stoichiometric equation for the combustion of 80%C:20%P optimized pellets [$C_{4.8}H_{5.49}O_{2.18}N_{0.0114}S_{0.0109}$] is given by Equation 16.

$$C_{4.8}H_{5.49}O_{2.18}N_{0.0114}S_{0.0109} + y_2[O_2 + (^{79}/_{21})N_2] \rightarrow p_2CO_2 + q_2H_2O + r_2SO_2 + [t_2 + y_2(^{79}/_{21})N_2] \quad (15)$$

The final stoichiometric combustion for 80%C:20%P optimized co-fired pellets.

$$C_{4.8}H_{5.49}O_{2.18}N_{0.0114}S_{0.0109} + 5.0934[O_2 + (^{79}/_{21})N_2] \rightarrow 5.0934CO_2 + 2.745H_2O + 0.0109SO_2 + 19.16N_2 \quad (16)$$

3.4.2.1 Wet and dry bases analyses of 80%C:20%P optimized co-fired pellet

From Equation 13, the total amount of wet products is 27.0102 kmol, while the total amount of dry products is 24.2643 kmol. Using Equation 13, the percentage composition of wet products is as follows: 18.86% CO_2, 10.16% H_2O, 0.04% SO_2, and 70.94% N_2. On dry analysis: 20.99% CO_2, 0.045% SO_2, and 78.96% N_2. Figures 3a and 3b present the 80%C:20%P co-fired pellets based on the wet and dry percentage composition of combustion emission gases.

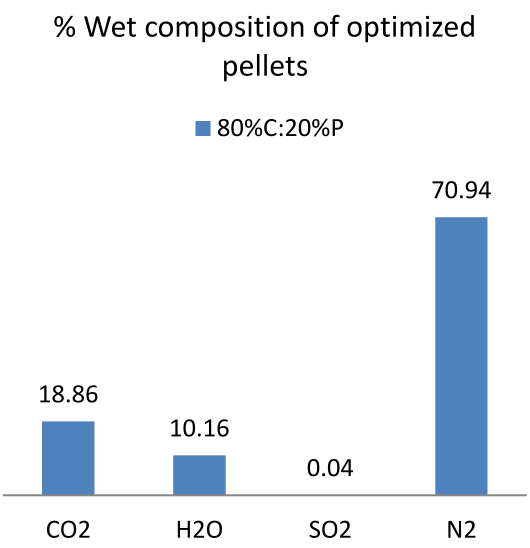

Figure 3a: Wet Composition Analysis

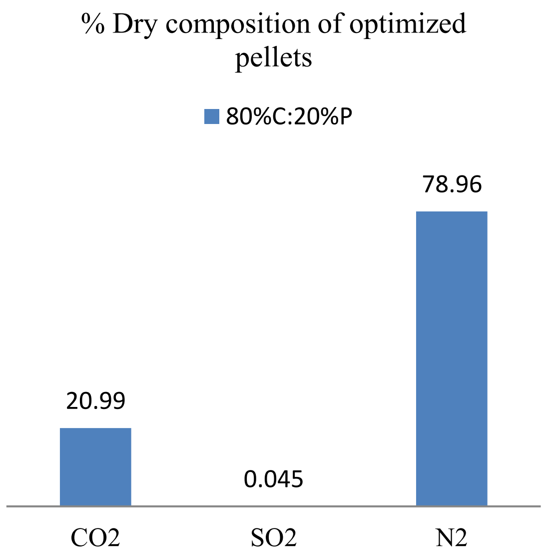

Figure 3b: Dry Composition Analysis

Figures 3a and 3b show that the 80%C:20%P optimized pellets have potential CO_2 emissions of 18.86% and SO_2 emissions of 0.04% on a wet basis, including nitrogen and water vapour, which account for 70.94% and 10.16%, respectively. On a dry basis, CO_2 and SO_2 emissions are 20.99% and 0.045%, respectively. The dry composition exhibited slightly higher emissions than the wet composition. This result reveals a significant reduction in combustion emissions of CO_2 and SO_2, indicating that an increase in the optimization ratio of PKS against CS has the potential to mitigate combustion emissions of CO_2 and SO_2. Similarly, both the wet and dry composition analyses validate Olatunde et al. [34] and the Bureau of Energy Efficiency, which suggested that SO_2 shouldn't be above 0.5% in fuel due to the high corrosion rate it causes in steam boilers.

3.4.3 Effect of 70%C: 30%P optimized co-fired pellet on combustion CO_2 and SO_2

The stoichiometric equation for the combustion of 70%C:30%P pellets [$C_{4.6}H_{5.43}O_{2.34}N_{0.0149}S_{0.0103}$] is given by Equation 17.

$$C_{4.6}H_{5.43}O_{2.34}N_{0.0149}S_{0.0103} + y_3[O_2 + (^{79}/_{21})N_2] \rightarrow p_3CO_2 + q_3H_2O + r_3SO_2 + [t_3 + y_3(^{79}/_{21})N_2]. \quad (17)$$

The final stoichiometric combustion for 70%C:30%P optimized co-fired pellets.

$$C_{4.6}H_{5.43}O_{2.34}N_{0.0149}S_{0.0103} + 4.798[O_2 + (^{79}/_{21})N_2] \rightarrow 4.6CO_2 + 2.715H_2O + 0.0103SO_2 + 18.05N_2 (18)$$

3.4.3.1 Wet and dry bases analyses of 70%C:30%P optimized co-fired pellet

From Equation 18, the total amount of wet products is 25.3753 kmol, while the total amount of dry products is 22.6603 kmol. Using Equation 13, the percentage composition of wet products is as follows: 18.13% CO_2, 10.70% H_2O, 0.041% SO_2, and 71.13% N_2. On dry analysis: 20.30% CO_2, 0.0455% SO_2, and 79.65% N_2. Figures 4a and 4b present the 70%C:30%P optimized pellets based on the wet and dry percentage composition of combustion emission gases.

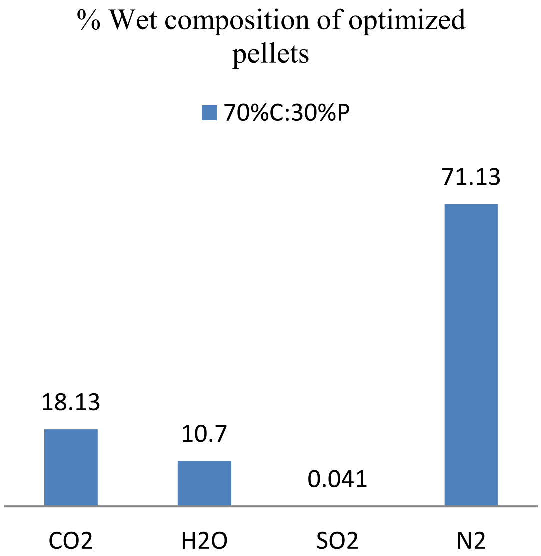

Figure 4a: Wet Composition Analysis

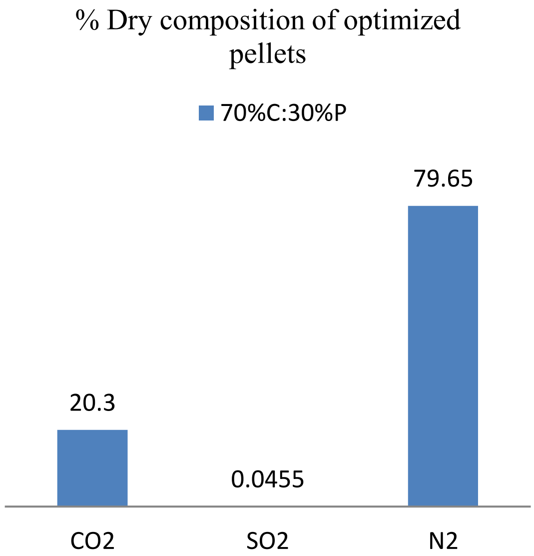

Figure 4b: Dry Composition Analysis

Figures 4a and 4b show that the 70%C:30%P optimized pellets have potential CO_2 emissions of 18.13% and SO_2 emissions of 0.041% on a wet basis, including nitrogen and water vapor, which account for 71.13% and 10.16%, respectively. On a dry basis, CO_2 and SO_2 emissions are 20.30% and 0.0455%, respectively. The dry composition exhibited slightly higher emissions than the wet composition. Comparatively, this result reveals a significant reduction in combustion CO_2 emissions compared to the 90%C:10%P and 80%C:20%P ratios, implying that an increase in the optimization ratio of PKS against CS has the potential to mitigate CO_2 emissions. However, there was no significant difference in SO_2 emissions between the 70%C:30%P and 80%C:20%P ratios. Again, the wet and dry analyses validate Olatunde et al. [34] and the Bureau of Energy Efficiency.

3.4.4 Effect of 60%C: 40%P optimized co-fired pellet on combustion CO_2 and SO_2

The stoichiometric equation for the combustion of 60%C:40%P optimized pellets [$C_{4.48}H_{5.38}O_{2.43}N_{0.0164}S_{0.0194}$] is given by Equation 19.

$$C_{4.48}H_{5.38}O_{2.43}N_{0.0164}S_{0.0194} + y_4[O_2 + (^{79}/_{21})N_2] \rightarrow p_4CO_2 + q_4H_2O + r_4SO_2 + [t_4 + y_4(^{79}/_{21})N_2] \quad (19)$$

The final stoichiometric combustion for 600%C:40%P optimized co-fired pellets.

$$C_{4.48}H_{5.38}O_{2.43}N_{0.0164}S_{0.0194} + 4.95[O_2 + (^{79}/_{21})N_2] \rightarrow 4.48CO_2 + 2.69H_2O + 0.0194SO_2 + 18.62N_2 \quad (20)$$

3.4.4.1 Wet and dry bases analyses of 60%C:4 0%P optimized co-fired pellet

From Equation 20, the total amount of wet products is 25.8094 kmol, while the total amount of dry products is 23.1194 kmol. Using Equation 13, the percentage composition of wet products is as follows: 17.36% CO_2, 10.42% H_2O, 0.075% SO_2, and 72.14% N_2. On a dry basis: 19.38% CO_2, 0.084% SO_2, and 80.54% N_2. Figures 5a and 5b present the 60%C:40%P optimized pellets based on the wet and dry percentage composition of combustion emission gases.

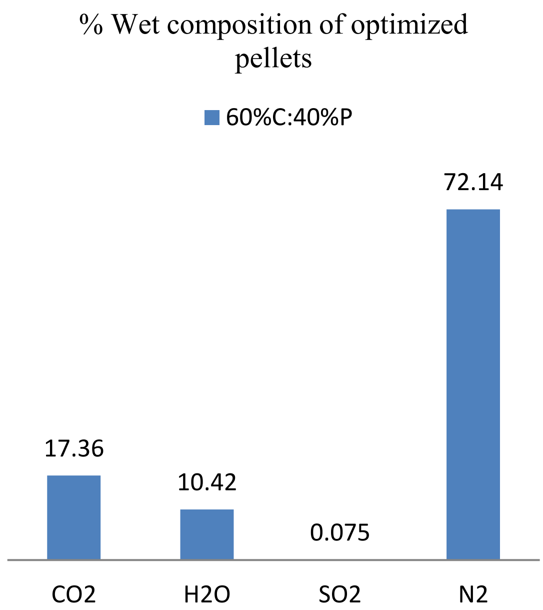

Figure 5a: Wet composition analysis

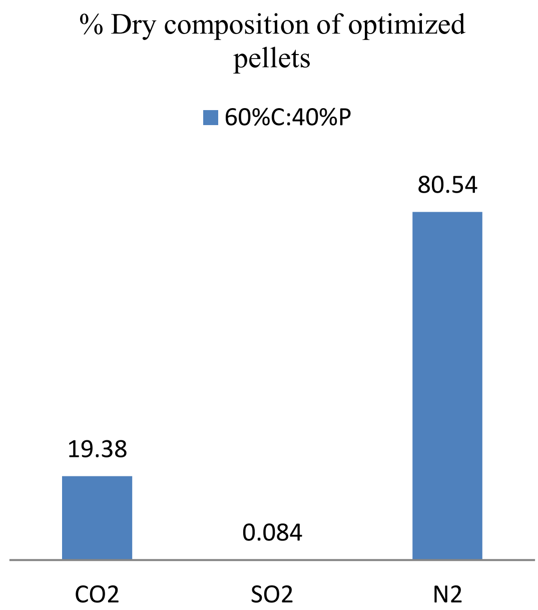

Figure 5b: Dry composition analysis

From Figures 5a and 5b, it was observed that the 60%C:40%P optimized pellets have potential CO_2 emissions of 17.36% and SO_2 emissions of 0.075% on a wet basis, including nitrogen and water vapour, which account for 72.14% and 10.42%, respectively. On a dry basis, CO_2 and SO_2 emissions are 19.38% and 0.084%, respectively. The dry composition exhibited slightly higher emissions than the wet composition. This result shows a significant reduction in combustion CO_2 emissions compared to the 90%C:10%P, 80%C:20%P, and 70%C:30%P ratios. This means that a continuous increase in the optimization ratio of PKS against CS has the potential to mitigate CO_2 emissions. However, it was observed that SO_2 emissions continue to rise as the optimization ratio of PKS increases against CS. This trend was revealed in the results for the 70%C:30%P, 80%C:20%P, and 90%C:10%P ratios. Nevertheless, the percentage wet and dry composition analyses validate Olatunde et al. [34] and the Bureau of Energy Efficiency.

3.4.5 Effect of 50%C: 50%P optimized co-fired pellet on combustion CO_2 and SO_2

The stoichiometric equation for the combustion of 50%C:50%P optimized pellets [$C_{4.28}H_{5.34}O_{2.56}N_{0.0179}S_{0.0081}$] is given by Equation 21.

$$C_{4.28}H_{5.34}O_{2.56}N_{0.0179}S_{0.0081} + y_5\left[O_2 + \left({}^{79}/_{21}\right)N_2\right] \rightarrow p_5CO_2 + q_5H_2O + r_5SO_2 + \left[t_5 + y_5\left({}^{79}/_{21}\right)N_2\right] \quad (21)$$

The final stoichiometric combustion for 50%C:50%P optimized co-fired pellets.

$$C_{4.28}H_{5.34}O_{2.56}N_{0.0179}S_{0.0081} + 4.936\left[O_2 + \left({}^{79}/_{21}\right)N_2\right] \rightarrow 4.28CO_2 + 2.67H_2O + 0.0081SO_2 + 18.57N_2 \quad (22)$$

3.4.5.1 Wet and dry bases analyses of 50%C:50%P optimized co-fired pellet

From Equation 21, the total amount of substance of wet products is 25.5281 kmol, while the total amount of substance of dry products is 22.8581 kmol. From Equation 13, the percentage composition of wet products is as follows: 16.77% CO_2, 10.46% H_2O, 0.032% SO_2, and 72.74% N_2. For the dry analysis, the composition is 18.72% CO_2, 0.035% SO_2, and 81.24% N_2. Figures 6a and 6b present the 50% C:50% P optimized pellets based on the wet and dry percentage composition of combustion emission gases.

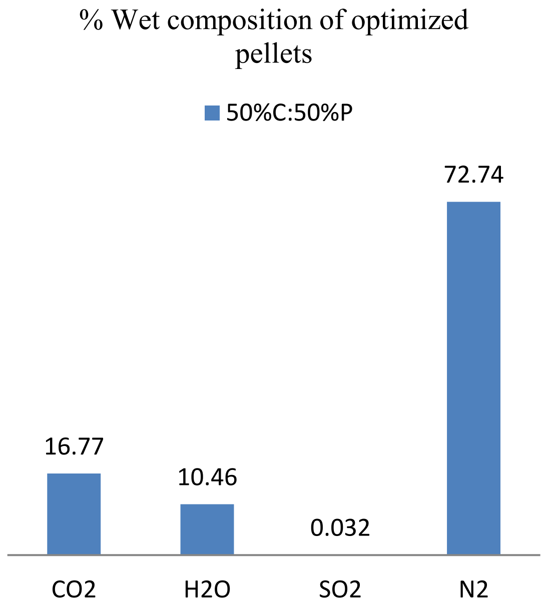

Figure 6a: Wet Composition Analysis

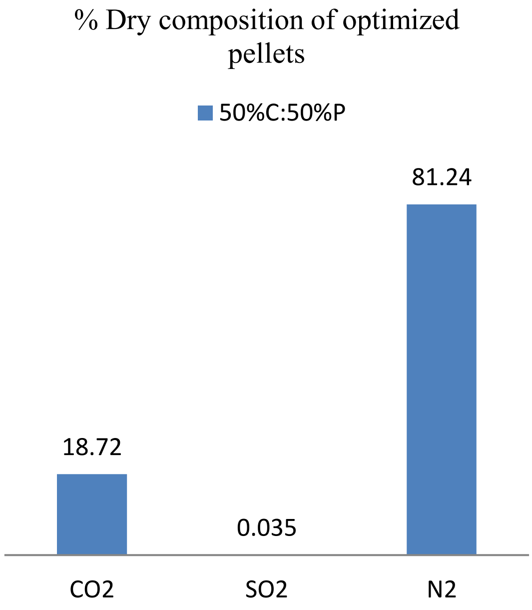

Figure 6b: Dry Composition Analysis

In Figure 6a, the 50% C:50% P optimized pellets exhibited 16.77% CO_2 emission and 0.032% SO_2 emissions on a wet basis, including 72.74% nitrogen and 10.46% water vapor. However, in Figure 6b, on a dry basis, it exhibited 18.72% CO_2 emission and 0.035% SO_2 emissions. As expected, the dry composition exhibited slightly higher emissions than the wet composition. More importantly, the 50% C:50% P mixture revealed a significantly higher reduction in combustion emissions of CO_2 and SO_2 on both wet and dry bases compared to the 90% C:10% P, 80% C:20% P, 70% C:30% P, and 60% C:40% P optimized pellets. Furthermore, this result validates the work of Olatunde et al. [34] and the Bureau of Energy Efficiency.

3.4.6 Effect of 90%P: 10%C optimized co-fired pellet on combustion CO_2 and SO_2
The stoichiometric equation for the combustion of 90%P:10%C optimized pellets [$C_{3.41}H_{5.13}O_{3.24}N_{0.0243}S_{0.0044}$] is given by Equation 23.

$$C_{3.41}H_{5.13}O_{3.24}N_{0.0243}S_{0.0044} + y_6\left[O_2 + \left({}^{79}/_{21}\right)N_2\right] \rightarrow p_6CO_2 + q_6H_2O + r_6SO_2 + \left[t_6 + y_6\left({}^{79}/_{21}\right)N_2\right] \tag{23}$$

The final stoichiometric combustion for 90%P:10%C optimized co-fired pellets.

$$C_{3.41}H_{5.13}O_{3.24}N_{0.00243}S_{0.0044} + 3.079\left[O_2 + \left({}^{79}/_{21}\right)N_2\right] \rightarrow 3.41CO_2 + 2.565H_2O + 0.0044SO_2 + 11.58N_2 \tag{24}$$

3.4.6.1 Wet and dry bases analyses of 90%P:10%C optimized co-fired pellet

From Equation 24, the total amount of substance of wet products is 17.5594 kmol, while the total amount of substance of dry products is 14.9944 kmol. From Equation 13, the percentage composition of wet products is as follows: 19.42% CO_2, 14.61% H_2O, 0.025% SO_2, and 65.95% N_2. For the dry analysis, the composition is 22.74% CO_2, 0.029% SO_2, and 77.23% N_2. Figures 7a and7b present the 90% P:10% C optimized pellets based on the wet and dry percentage composition of combustion emission gases.

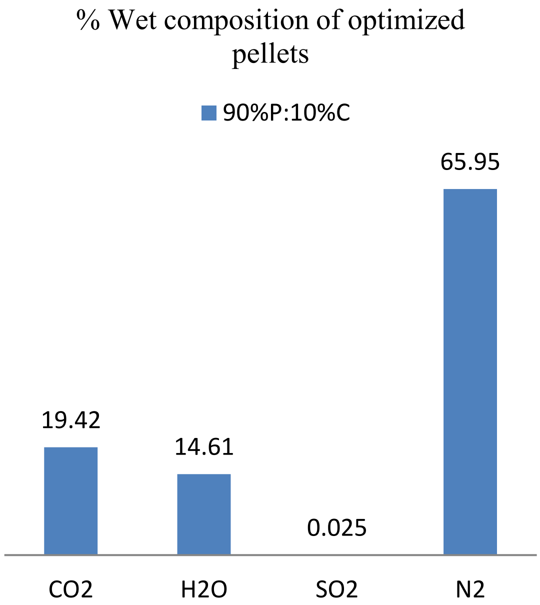

Figure 7a: Wet composition analysis

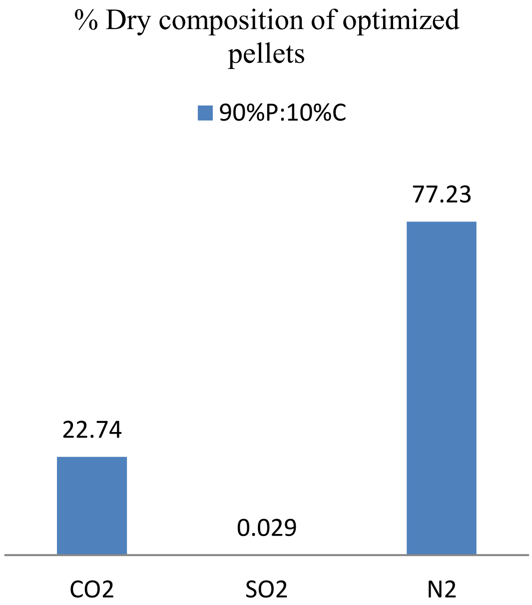

Figure 7b: Dry composition analysis

In Figure 7a, the 90% P:10% C optimized pellets exhibited 19.42% CO_2 emissions and 0.025% SO_2 emissions on a wet basis, including 65.95% nitrogen and 14.61% water vapour. However, on a dry basis, Figure 7b exhibited 22.74% CO_2 emissions and 0.029% SO_2 emissions. Again, as expected, the dry composition is slightly higher than the wet composition. More importantly, the 90% P:10% C mixture revealed a significant reduction in combustion emissions of SO_2 on both wet and dry bases compared to the 90% C:10% P, 80% C:20% P, 70% C:30% P, 60% C:40% P, and 50% C:50% P optimized pellets. Furthermore, it was also observed that as the optimization ratio of PKS against the CS increases, the percentage composition of CO_2 reduces while that of SO_2 increases slightly. In other words, CS has more potential in SO_2 mitigation. Nevertheless, all percentage compositions of CO_2 and SO_2 validate the work of Olatunde et al. [34] and the Bureau of Energy Efficiency.

3.4.7 Effect of 80%P: 20%C optimized co-fired pellet on combustion CO_2 and SO_2

The stoichiometric equation for the combustion of 80%P:20%C optimized pellets [$C_{3.63}H_{5.18}O_{3.08}N_{0.0229}S_{0.0056}$] is given by Equation 26.

$$C_{3.63}H_{5.18}O_{3.08}N_{0.0229}S_{0.0056} + y_7\left[O_2 + \left({}^{79}/_{21}\right)N_2\right] \rightarrow p_7CO_2 + q_7H_2O + r_7SO_2 + \left[t_7 + y_7\left({}^{79}/_{21}\right)N_2\right] \quad (25)$$

The final stoichiometric combustion for 80%P:20%C optimized co-fired pellets.

$$C_{3.63}H_{5.18}O_{3.083}N_{0.0229}S_{0.0056} + 3.376\left[O_2 + \left({}^{79}/_{21}\right)N_2\right] \rightarrow 3.63CO_2 + 2.56H_2O + 0.0056SO_2 + 12.70N_2 \quad (26)$$

3.4.7.1 Wet and dry bases analyses of 80%P:20%C optimized pellet

From Equation 26, the total amount of substance of wet products is 18.8956 kmol, while the total amount of substance of dry products is 16.3356 kmol. From Equation 13, the percentage composition of wet products is as follows: 19.21% CO_2, 13.55% H_2O, 0.03% SO_2, and 67.21% N_2. On a dry basis, the analysis yields 22.22% CO_2, 0.034% SO_2, and 77.74% N_2. Figures 8a and 8b present 80%P:20%C optimized pellets based on the wet and dry percentage composition of combustion emission gases.

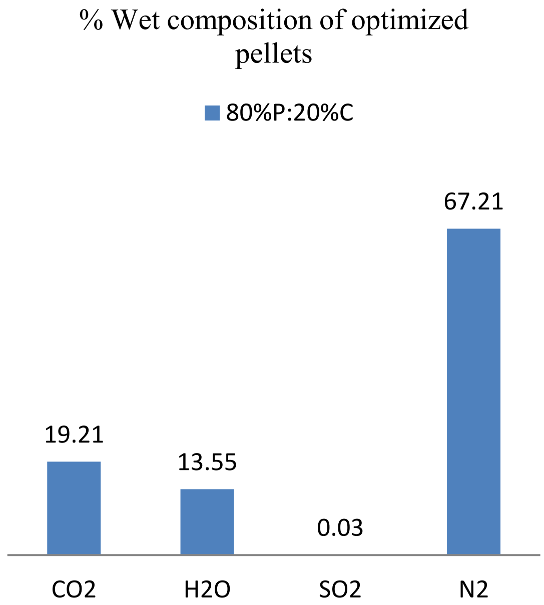

Figure 8a: Wet Composition Analysis

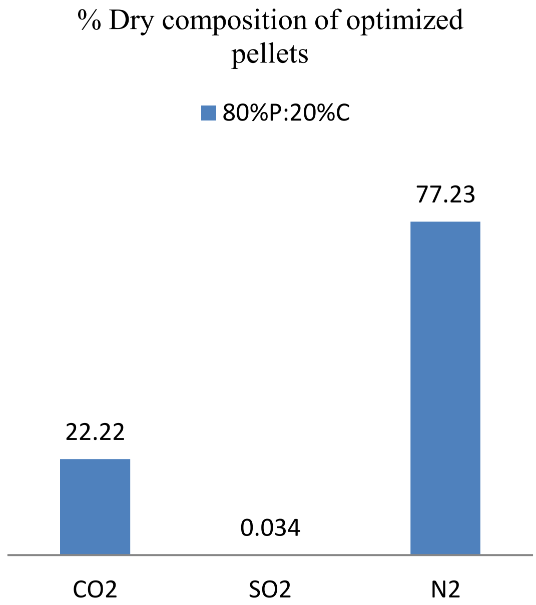

Figure 8b: Dry Composition Analysis

In Figure 8a, the 80%P:20%C optimized pellets exhibited 19.21% CO_2 emissions and 0.03% SO_2 emissions on a wet basis, including 67.21% nitrogen and 13.55% water vapor. However, on a dry basis, Figure 8b exhibited 22.22% CO_2 emissions and 0.034% SO_2 emissions. As expected, the dry composition is slightly higher than the wet composition. The 80%P:20%C revealed a reduction in combustion CO_2 emissions on both wet and dry basis analyses compared to the 90%C:10%P, 80%C:20%P, 70%C:30%P, 60%C:40%P, 50%C:50%P, and 90%P:10%C optimized pellets. Additionally, it was observed that as the optimization ratio of PKS against the CS increases, the percentage composition of CO_2 emissions continues to decrease while the SO_2 emissions increase slightly.

3.4.8 Effect of 70%P: 30%C optimized co-fired pellet on combustion CO_2 and SO_2

The stoichiometric equation for the combustion of 70%P:30%C optimized pellets [$C_{3.77}H_{5.24}O_{2.97}N_{0.0207}S_{0.0063}$] is given by Equation 27.

$$C_{3.77}H_{5.24}O_{2.97}N_{0.0207}S_{0.0063} + y_8\left[O_2 + \left({}^{79}/_{21}\right)N_2\right] \rightarrow p_8CO_2 + q_8H_2O + r_8SO_2 + \left[t_8 + y_8\left({}^{79}/_{21}\right)N_2\right] \quad (27)$$

The final stoichiometric combustion for 70%P:30%C optimized co-fired pellets.

$$C_{3.77}H_{5.24}O_{2.97}N_{0.0207}S_{0.0063} + 3.6013\left[O_2 + \left({}^{79}/_{21}\right)N_2\right] \rightarrow 3.60138CO_2 + 2.62H_2O + 0.0063SO_2 + 13.55N_2 \quad (28)$$

3.4.8.1 Wet and dry bases analyses of 70%P:30%C optimized pellet

From Equation 28, the total amount of substance of wet products is 19.778 kmol, while the total amount of substance of dry products is 17.158 kmol. From Equation 13, the percentage composition of wet products is as follows: 18.21% CO_2, 13.25% H_2O, 0.032% SO_2, and 68.51% N_2. On a dry basis, the analysis yields 20.99% CO_2, 0.037% SO_2, and 78.97% N_2. Figures 9a and 9b present 70%P:30%C optimized pellets based on the wet and dry percentage composition of combustion emission gases.

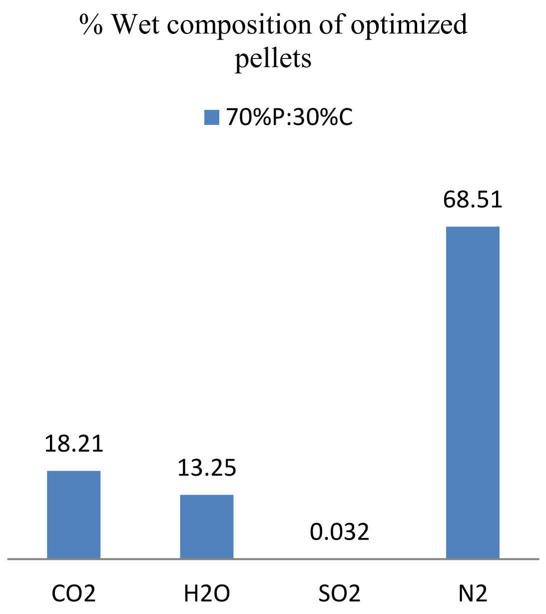

Figure 9a: Wet composition analysis

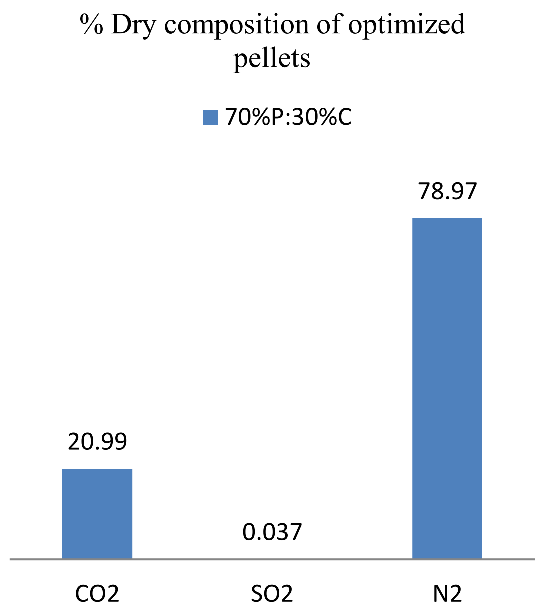

Figure 9b: Dry composition analysis

In Figure 9a, the 70%P:30%C optimized pellets exhibited 18.21% CO_2 emissions and 0.032% SO_2 emissions on a wet basis, including 68.51% nitrogen and 13.25% water vapor. However, on a dry basis, Figure 9b exhibited 20.99% CO_2 emissions and 0.037% SO_2 emissions. As expected, the dry composition is slightly higher than the wet composition. The 70%P:30%C revealed a reduction in combustion CO_2 emissions on both wet and dry basis analyses compared to the 90%C:10%P, 80%C:20%P, 70%C:30%P, 60%C:40%P, 50%C:50%P, 90%P:10%C, and 80%P:20%C optimized pellets. Additionally, it was observed that as the optimization ratio of PKS against CS increases, the percentage composition of CO_2 emissions continues to decrease while the SO_2 emissions increase slightly.

3.4.9 Effect of 60%P: 40%C optimized co-fired pellet on combustion CO_2 and SO_2

The stoichiometric equation for the combustion of 60%P:40%C optimized pellets [$C_{4.01}H_{5.30}O_{2.79}N_{0.0193}S_{0.0069}$] is given by Equation 29.

$$C_{4.01}H_{5.30}O_{2.79}N_{0.0193}S_{0.0069} + y_9\left[O_2 + \left({}^{79}/_{21}\right)N_2\right] \rightarrow p_9CO_2 + q_9H_2O + r_9SO_2 + \left[t_9 + y_9\left({}^{79}/_{21}\right)N_2\right] \quad (29)$$

The final stoichiometric combustion for 60%P:40%C optimized co-fired pellets.

$$C_{4.01}H_{5.30}O_{2.79}N_{0.0193}S_{0.0069} + 3.9469\left[O_2 + \left({}^{79}/_{21}\right)N_2\right] \rightarrow 4.01CO_2 + 2.65H_2O + 0.0069SO_2 + 14.85N_2 \quad (30)$$

3.4.9.1 Wet and dry bases analyses of 60%P:40%C optimized pellet

From Equation 30, the total amount of substance of wet products is 21.517 kmol, while the total amount of substance of dry products is 18.867 kmol. From Equation 13, the percentage composition of wet products is as follows: 18.64% CO_2, 12.32% H_2O, 0.032% SO_2, and 69.02% N_2. On a dry basis, the analysis yields 21.25% CO_2, 0.037% SO_2, and 78.71% N_2. Figures 10a and 10b present 60%P:40%C optimized pellets based on the wet and dry percentage composition of combustion emission gases.

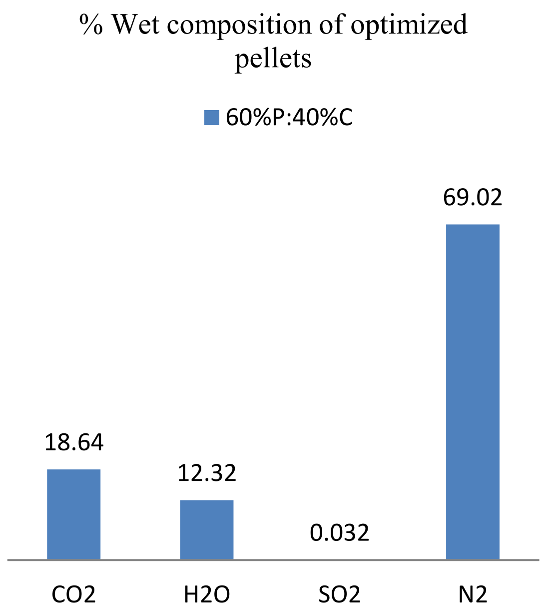

Figure 10a: Wet composition analysis

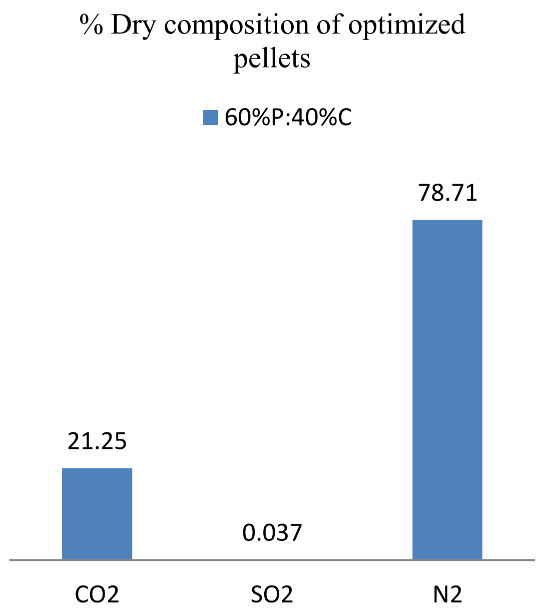

Figure 10b: Dry composition analysis

In Figure 10a, the 60%P:40%C optimized pellets exhibited 18.64% CO_2 emissions and 0.032% SO_2 emissions on a wet basis, including 69.02% nitrogen and 12.32% water vapour. However, on a dry basis, Figure 10b exhibited 21.25% CO_2 emissions and 0.037% SO_2 emissions. As expected, the dry composition is slightly higher than the wet composition. Similarly, the 60%P:40%C revealed a reduction in CO_2 emissions on both wet and dry basis analyses compared to the other optimized pellets. Furthermore, it was observed that as the optimization ratio of PKS to CS increases, the percentage composition of CO_2 emissions continues to decrease while the SO_2 emissions slightly increase.

3.5 Comparative Analysis of CO_2 and SO_2 Emissions of the Models of Optimized Pellets

3.5.1 Wet and Dry CO_2 Emissions of Model I Compared to Model II

Figures 11a and 11b present a comparative analysis of CO2 emissions of Model I and Model II on a wet basis.

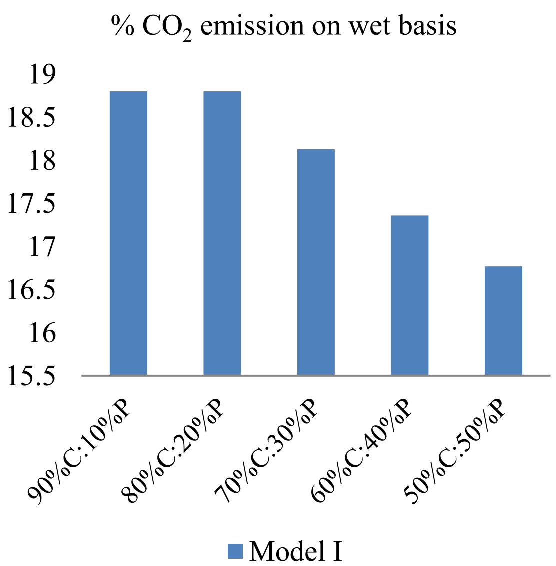

Figure 11a: Wet Basis of Model I

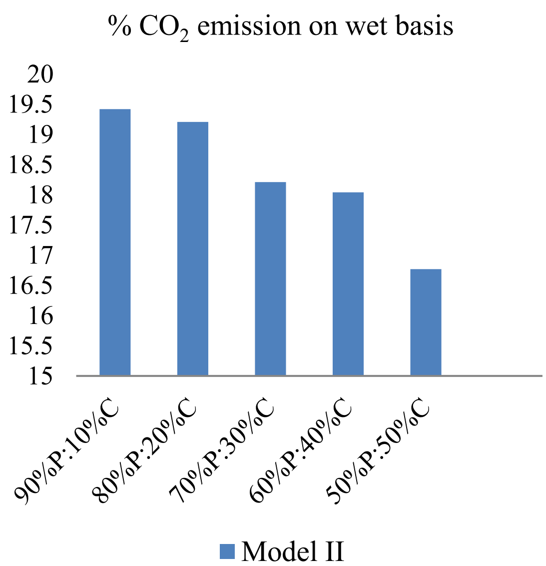

Figure 11b: Wet Basis of Model II

Figures 12a and 12b present the comparative analysis emission CO_2 of Model I and II on dry basis.

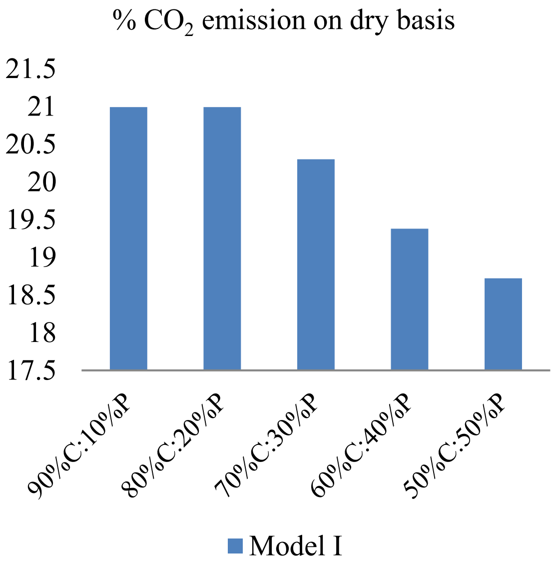

Figure 12a: Dry Basis of Model I

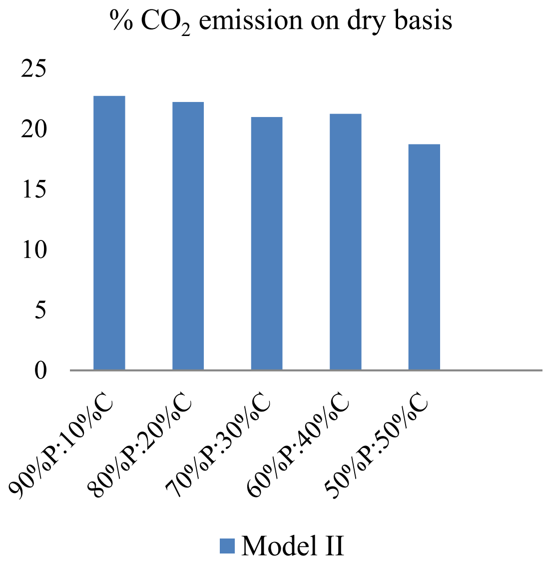

Figure 12b: Dry Basis of Model II

Figures 11a, 11b, 12a, and 12b present the wet and dry CO_2 emissions of Model I and Model II of the optimized pellets. Figures 11a and 11b (Model I and II) revealed that the 50%:50% optimization ratio has the lowest and same percentage of CO_2 emission at 16.77% on a wet basis. Similar results were obtained and replicated in Figures 12a and 12b, with an 18.72% composition of CO_2 emission on a dry basis. Essentially, Models I and II showed that on both wet and dry bases, the 50%:50% optimization ratio of the biomass residues (i.e., PKS and CS) has a greater potential for mitigating combustion CO_2 emissions than other optimization ratios with relatively higher values. The results also showed that emissions were more favourable on a wet basis. Comparatively, Model I exhibited more favourable CO_2 emissions than Model II on both wet and dry bases.

3.5.2 Wet and Dry Combustion Emission SO_2 of Model I against Model II

Figures 13a and 13b present comparative analysis of emission SO_2 of Model I and II on wet basis.

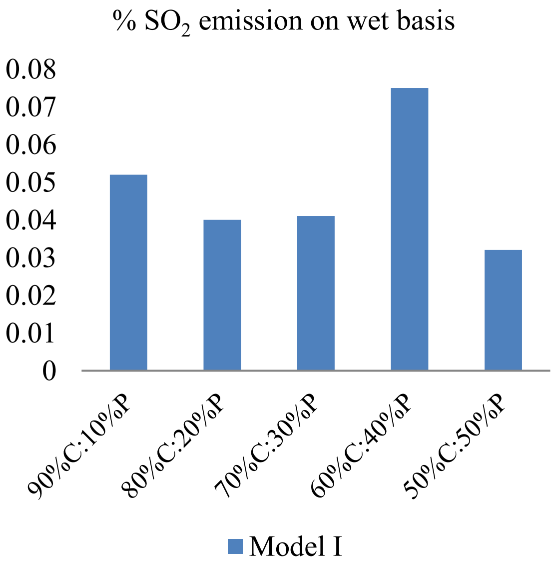

Figure 13a: Wet Basis of Model I

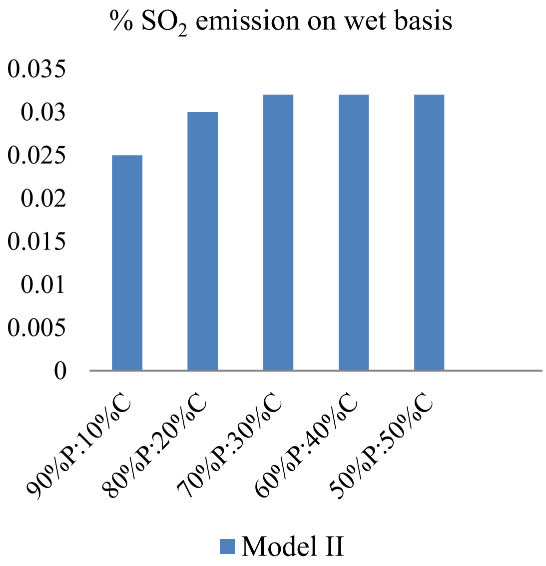

Figure 13b: Wet Basis of Model II

Figures 14a and 14b present the comparative analysis emission SO_2 of Model I and II on dry basis.

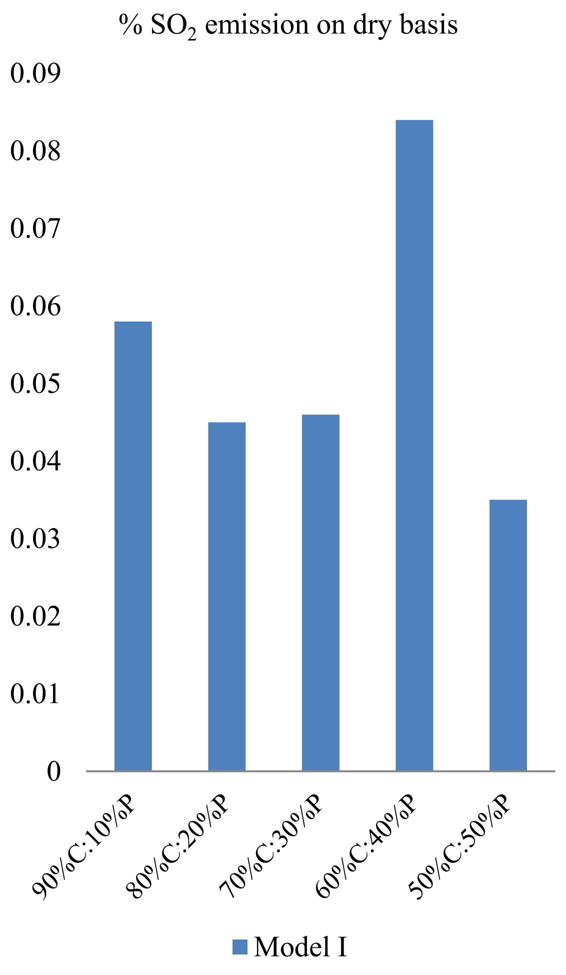

Figure 14a: Dry Basis of Model I

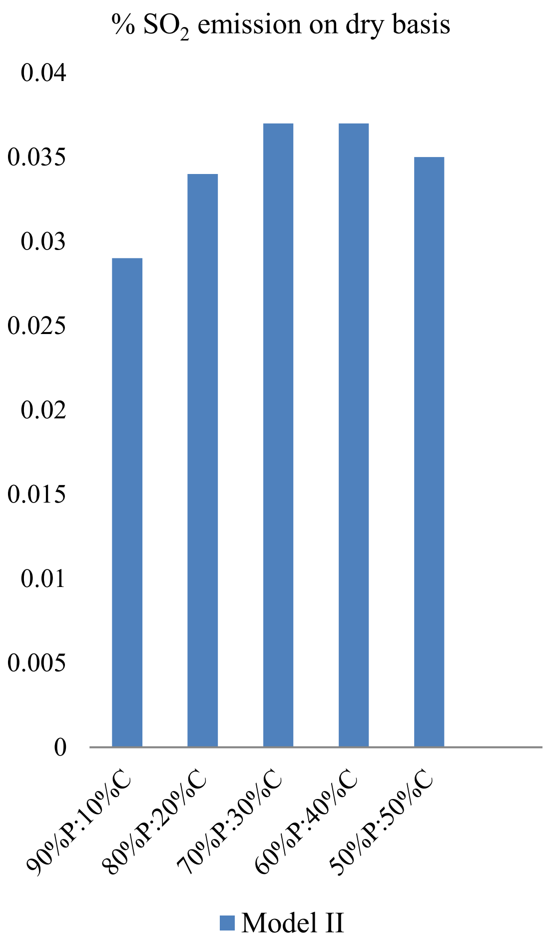

Figure 14b: Dry Basis of Model II

Again, in Figures 13a, 13b, 14a, and 14b, results were presented for the wet and dry SO_2 emissions of Models I and II of the optimized pellets. Figures 13a and 13b (Model I and II) revealed that the 50%:50% optimization ratio has the lowest and same percentage of SO_2 emissions at 0.032%. Similarly, this was replicated in Figures 14a and 14b, with 0.035% SO_2 emissions. Both Models I and II showed that on both wet and dry bases, the 50%:50% optimization ratio of the biomass residues (i.e., PKS and CS) has greater potential in mitigating combustion SO_2 emissions. Comparatively, on both wet and dry bases, Model II exhibited more favourable SO_2 emissions compared to Model I.

3.6 Findings in this study

In terms of combustion sustainability and efficiency, the best optimal mixing ratio for the production of cofiring pellets is 90%C:10%P based on the higher calorific value obtained, the percentage carbon in the ultimate analysis (Table 3a) and the percentage volatile matter (VM) in the proximate analysis (Tables 2a & 2b). However, the focus of this study is to establish the optimal mixing ratio for mitigating combustion emission CO_2 and SO_2 which the 50%C:50%P cofired pellet in Model I and 50%P:50%C in Model II demonstrated. The study therefore identified significant findings as follows:

- In Model I, CO_2 emission remained relatively higher between 90%C:10%P and 80%C:20%P optimization ration but began to decrease as the ratio of CS to PKS began to shift towards 50%C:50%P. In other words, the lower the percentage ratio of CS to PKS, the lower the CO_2 emission. Similarly, in Model II, CO_2 emissions continued to reduce with decrease in percentage ratio of CS to PKS (i.e. 90%P:10%C to 60%P:40%C). That is to say that the PKS constituent in the cofired pellet influences the low CO_2 emission while the CS constituent influences higher emission of CO_2.
- However, in Model I, SO_2 emissions was relatively lower between 90%C:10%P and 80%C:20%P optimization ratio but slightly began to increase as the percentage ratio of CS to PKS increased from 70%C:30%P to 60%C:40%P. In other words, the higher the percentage ratio of CS to PKS, the higher the SO_2 emission. Similarly, in Model II, SO_2 emissions increased initially and thereafter, stabilized from 70%P:30%C to

60%P:40%C. Again, this implies that the PKS constituent in the cofired pellet influences higher SO_2 emission while the CS constituent influences lower SO_2 emission.

- Essentially, in Models I & II respectively, it was observed that there was drastic reductions in both CO_2 and SO_2 emissions at the 50%C:50%P optimization ratio on both wet and dry analyses aligning with Bureau of Energy Efficiency guidelines. This could be due to a balance between the both constituents in the cofired pellet.

These findings underscore the potential of varying CS and PKS ratios in optimizing combustion emissions in a Biomass Power Plant, highlighting the effectiveness of CS's in SO_2 reduction and PKS in CO_2 reduction while supporting previous research and energy efficiency standards.

3.7 Applications of Optimized Pellets for Industrial and Domestic Purposes

As earlier stated and discussed in section 3.1, optimized cofired pellets can be implemented in industrial or domestic application. For instance, in the industries where high temperature and pressure steam is required for their processing and/or power generation, the optimal mixing ratio of 90%C:10%P must be applied for the production of cofired pellets. This will enable effective combustion performance, efficiency and sustainability. It is also important to note that adequate quality pellets (i.e. high CV and VM) improves sustainability of fuel combustion. In other words, less fuel is required for combustion process unlike when the CV is low. However, if for any reason (s), there is abundance supply of palm kernel shell over coconut shell; therefore, the 60%P:40%C optimized mixing ratio with CV of 30, 598 kJ/kg could serve as an alternative for improved combustion performance and sustainability.

4. Conclusion

This study explored the impact of optimization ratios on the combustion performance of tropical co-fired biomass pellets, employing two distinct models. Experimental findings and combustion performance analyses demonstrated that the 50%:50% optimization ratio in both Model I and II consistently yielded the lowest CO_2 and SO_2 emissions percentages on wet and dry bases. This underscores its efficacy in mitigating combustion emissions compared to other ratios tested, which exhibited higher emissions values. Furthermore, results indicated that emissions were generally more favourable on wet bases than on dry bases. Model I exhibited superior potential in CO_2 mitigation, while Model II showed greater effectiveness in SO_2 reduction. Thus, depending on whether the focus is on CO_2 or SO_2 mitigation, Model I or Model II should be selected for optimization efforts, respectively. These findings provide valuable insights into optimizing biomass residues such as PKS and CS for enhanced environmental performance in combustion applications.

Conflict of Interest

The authors have no competing interests to declare that are relevant to the content of this article.

References

[1] Casaca C, Costa M (2003): Co-Combustion of Biomass in a Natural Gasifired Furnace. Combust. Sci. and Tech., DOI: 10.1080/00102200390241664
[2] Obaidullah M, Bram S, VermaV. K, De RuyckJ (2012): A Review on Particle Emissions from Small Scale Biomass Combustion. International Journal of Renewable Energy Research. Vol.2, No.1, 2012
[3] Hamelinck C N, Suurs R A A, Faaij A P C (2005): International Bioenergy Transport Costs and Energy Balance. Biomass and Bioenergy; 29:114-34.
[4] Khan A A, Jong W D, Jansens P J, Spliethoff H (2009): Biomass Combustion in Fluidized Bed Boilers: Potentials, Problems and Remedies. Fuel Processing Technology; 90:21-50.
[5] Hoogwijk M M, Faaij A P C, Broek R V D, Berndes G, Gielen D, Turkenburg W C (2003): Exploration of the ranges of the Global Potential of Biomass for Energy. Biomass and Bioenergy; 25(2):119-33.
[6] Demirbas M F, Balat M, Balat H (2009): Potential Contribution of Biomass to the Sustainable Energy Development. Energy Conversion and Management; 50:1746-60.
[7] Saidur R, Abdelaziz E A, Demirbas A, Hossain M S, Mekhilef S (2011): A Review of Biomass as Fuel for Boilers. Renewable Energy and Sustainable Energy Reviews; 15:2262-89
[8] Guisson R, Marchal D (2009): IEA Bioenergy Task 40-Country Report Belgium. September 2009.
[9] Verma V. R, Bram S, Delattin F, Laha P, Vandendael I, Hubin A, De Ruyck J (2011): Agro-Pellets for Domestic Heating Boilers: Standard Laboratory and Real Life Performance. Applied Energy:1-8.
[10] Tissari J, Sippula O, Kouki J, Vuorio K, Jokiniemi J (2008): Fine Particle and Gas Emissions from the Combustion of Agricultural Fuels Fired in a 20 kW Burner. Energy & Fuels;22:2033-42.
[11] Yin C, Rosendahl L. A, Kær S. K (2008): Grate-Firing of Biomass for Heat and Power Production. Prog. Energy Combust Sci.;34:725–54.

[12] Zhang X, Chen Q, Bradford R, Sharifi V, Swithenbank J (2010): Experimental Investigation and Mathematical Modelling of Wood Combustion in a Moving Grate Boiler. Fuel Process Technology;91:1491–9
[13] Hamid Sefidari, NargesRazmjoo, Michael Strand (2014): An Experimental Study of Combustion and Emissions of Two Types of Woody Biomass in a 12-MW Reciprocating-Grate Boiler. FUEL 135, 120- 129
[14] Barcelos, E.; Rios, S.D.A.; Cunha, R.N.; Lopes, R.; Motoike, S.Y.; Babiychuk, E.; Skirycz, A.; Kushnir, S (2015): Oil Palm Natural Diversity and the Potential for Yield Improvement. Front. Plant Sc, 6, 190.
[15] Wang Z, Hong C, Xing Y, Li Y, Feng L and Jia M (2018): Combustion Behaviours and Kinetics of Sewage Sludge Blended with Pulverized Coal: With and without Catalysts. Waste Manag. 74 (2) 88–96
[16] Onochie U. P,Otomi K O, Adingwupu, A. C, Ikpeseni S.C, Owamah H. I (2021):Assessment of Power Generation Potential from the Cofiring of ElaeisGuineensis Residues with Coal Pellets in a Popular Nigerian Palm Oil Research Institute.International
[17] Khalidah Al-Qayim, William Nimmo1, Mohammed Pourkashanian(2019): Effect of Oxy-fuel Combustion on Ash Deposition of Pulverized Wood Pellets Research Journal 21 927-936
[18] Rohan Fernando (2012):Cofiring High Ratios of Biomass with Coal. IEA Clean Coal Centre
[19] Baxter Larry (2005): Biomass-Coal Co-combustion: Opportunity for Affordable Renewable Energy. Fuel 84 1295–1302
[20] Vamvuka N, Pasadakis E, Kastanaki P, Grammelis E K (2003): Kinetic Modelling of Coal/Agricultural byProduct Blends, Energy. Fuel 17 549-558
[21] Tahir, J., Ahmad, R. and Tian, Z., (2023): Calorific Value Prediction Models of Processed Refuse Derived Fuel using Ultimate Analysis. Biofuels, 14 (1), pp.69-78
[22] Nguyen, H., Bui, H. B., & Bui, X. N. (2021): Rapid Determination of Gross Calorific Value of Coal using Artificial Neural Network and Particle Swarm Optimization. Natural Resources Research, *30*, 621-638.
[23] Oji Akuma, Monday Charles (2017): Themed Section: Science and Technology 30 Characteristic Analysis of Bio-coal Briquette (Coal and Groundnut Shell Admixtures); Volume 3, Issue 3
[24] Maciejewska, A., Veringa, H., Sanders, J., &Peteve, D. (2006): Co-firing of Biomass with Coal Constraints and Role of Biomass. International Journal of Biomass and Constraint, Vol. 79. (34). Pp. 786-789.
[25] Kakooza A W. (2017): Appraisal of Food Residue (Waste) Based Fuel Briquettes in Domestic Cooking Applications: A Case Study of Uganda.
[26] Oyelaran O A, Olorunfemi B J, Sanusi O M (2018): Investigating the Performance and Combustion Characteristics of Composite Bio-coal Briquette. Journal of Materials and Engineering Structures, 2018, 5: 173-184.
[27] Baral A R, Shrestha K R (2018): Properties of briquettes and pellets of pine needles from Hattiban Community Forest, Kathmandu, Nepal[J/OL]. Nepal Journal of Environmental Science, 6: 1-8. DOI: https://doi.org/10.3126/njes.v6i0.30115
[28] Loo S. V, and Koppejan J. (2008): The Handbook of Biomass Combustion and Co-firing, London: Earthscan
[29] Japhet J. A, Tokan A, and Muhammad M. H (2015): Production and Characterization of Rice Husk Pellet", American J Eng. Res 4112-119
[30] Onochie U. P, Ofomatah A. C, Onwurah C, Tyopine A. A, Akingba O. O, Kubeynje B. F, Aluma C. C, Alozie C (2023): Potentials of Biomass Waste Resources with Respect to their Calorific Value, Proximate and Ultimate Analysis for Energy Utilization. *IOP* Conf. Series: Earth and Environmental Science 1178 (2023) 012012 https://doi:10.1088/1755-1315/1178/1/012012
[31] Mitchual S.J, Frimpong-Mensah K, Darkwa N.A (2014): Journal of Sustainable Bioenergy System 4 50
[32] Gil R.R, Giron R.P, Lozano M.S, Ruiz B, Fuente E (2012): J. Anal. Appl. Pyrolysis 98 129
[33] Onochie U. P, Obanor A.I, Aliu S. A, Ighodaro O.O (2017): Proximate and Ultimate Analysis Obtained from Fuel Pellets Produced from Oil Palm Residues. Nigeria Journal of Technology (NIJOTECH) 36 987-990
[34] Olatunde A. O, Faralu M. S, Olawale M. S, Olusegun B, and Adeyinka O. F(2017): Energy Potentials of Briquette Produced from Tannery Solid Waste Makara J. Technol. 21 122-128
[35] Lizica S. P, Alexandru S. B, Spiru P (2020): Calculation of Combustion Air Required for Burning Solid Fuels (Coal / Biomass / Solid Waste) and Analysis of Flue Gas Composition. Energy Reports, Volume 6,Supplement 3, Pages 36-45

[36] Ramesh. T , Sathiyagnanam .A.P, Melvin V,P. Murugan (2022): A Comprehensive Study on the Effect of Dimethyl Carbonate Oxygenate and EGR on Emission Reduction, Combustion Analysis and Performance Enhancement of a CRDI Diesel Engine Using a Blend of Diesel and ProsopisJuliflora Biodiesel. International Journal Of Chemical Engineering .Volume 2022, Article Id 5717362, 12 Pages. Https://Doi.Org/10.1155/2022/5717362

[37] Anufriev .I. S, E. P. Kopyev, I. S. Sadkin, M. A. Mukhina (2021): Diesel and Waste Oil Combustion in a New Steam Burner with Low No_x Emission. Fuel, Volume 290,2021,120100,Issn 0016-2361, https://Doi.Org/10.1016/J.Fuel.2020.120100