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Optimisation of Ash Yield and CO Emission in Co-Combustion of Torrefied Palm Kernel-Cashew Nut Shells

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Abstract
Combustion of solid biofuels generates significant ash residues and harmful emissions, posing substantial threats to both environmental sustainability and human comfort. This study aimed to achieve minimum ash yield (AY) and carbon oxide (CO) emission in the co-combustion process of torrefied palm kernel shells (TPKS) and cashew nut shells (TCNS) mixed with kaolin additive (KA) in a tubular furnace. Optimisation of components mixture and factors like temperature, particle size and residence time were conducted. The optimisation was achieved by utilising the custom design methodology (CDM) of Design Expert software (version 13). Ash yield of the TPKS-TCNS fuel mixture, with and without the additive, was analysed using X-ray Diffractometer (XRD) to identify the mineral phase compounds within the ash. The optimised composition consisted of TPKS (69.6%), TCNS (23.3%) and KA (7.1%) at 900 ⁰C, with a particle size of 1.00 mm and a residence time of 120 min. The composition yielded the lowest AY (10.10%) and CO (209 ppm). XRD analysis revealed a decrease in (K-Na-Ca-Mg-Fe-Al-) compounds and a significant increase in SiO_2 with the disappearance of KCl peaks upon adding kaolin. The presence of SiO_2 in the ash confirmed the reduction reaction between K salts and chlorides. The study suggests that adding kaolin holds promise for reducing AY and CO emissions. Thus, enhancing the efficiency of TPKS and TCNS combustion in a grate furnace was recorded.

Keywords: *Ash yield, co-emission, combustion, kaolin additive, palm kernel-cashew nut shells.*

1.0 Introduction

Energy remains a challenge confronting every continent of the world. A pragmatic approach is required of every nation and sub-continent to look beyond the box in searching for energy generation more economically. Agro-wastes are always treated as materials with zero economic value, especially in developing countries. Agro-wastes in the form of feedstock, nut shells and husks can add about 100–400 EJ per year to the global energy supply (Cheah et al., 2022). Waste agricultural residues are frequently combusted in industries for heat and power generation. However, standalone biomass combustion often struggles with achieving high combustion efficiency, which can lead to challenges such as reduced boiler performance and slag formation on auxiliary equipment. To mitigate these issues, co-firing biomass with additives has emerged as a promising alternative. Palm kernel shell (PKS), a by-product of the oil palm industry known for its high calorific value, is commonly used to fuel boilers for steam and electricity generation (Kareem et al., 2018). Despite its high alkali content, palm kernel shell (PKS) is susceptible to bed agglomeration during combustion in a fluidised bed. Nonetheless, the ashes produced from PKS are currently utilised in engineering applications, such as the reinforcement of concrete in the construction industry (Chungcharoen & Srisang, 2020).

Cashew nut shells liquid (CNSL) contains consistent that leaches into the soil or water due to their toxicity. Once the CNSL is extracted, the remaining de-oiled cashew nut shells. This accounts for approximately 50% by weight of the nut, which is abundant as biomass waste. These shells possess a calorific value of about 4252 kcal/kg and are utilised in various applications including charcoal production and steam generation (Shao et al., 2012). In addition, PKS and CNS present versatile opportunities for utilisation, including energy generation, biomass fuel production and incorporation into animal feed formulations (Li et al., 2012).

In an investigation, palm shell, mesocarp fibre and bunches of palm fruit were dehydrated and torrefied at temperatures < 105 °C and 200–300 °C, respectively at a resident time of 120 min. An increment in calorific value and carbon composition of 23 MJ/kg and 58.7% were obtained for PKS, respectively (Sabil et al., 2013). Another study affirmed that torrefaction is an economical means of optimising energy sourced from solid biomass waste. The study emphasised the deficiencies in solid waste as high moisture content, hygroscopic, low calorific content, grindability, non-uniform shape and size (Lasek et al., 2023). Whereas, another study

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underscored the application of zeolite cracking, steam reformation, esterification and catalytic hydrodeoxygeneration as means of rectifying the deficiencies inherent in biofuel soured through the pyrolysis technique (Cheah et al., 2022).

Similarly, Nigeria is one of the leading countries in palm oil production, generates over 1.03 million metric tons of PKS yearly (Ninduangdee & Kuprianov, 2014). These residues have low bulk density and varying sizes and shapes. The residues are often disposed of by open-air burning or landfill deposition, leading to the release of greenhouse gases such as CO_2, CH_4 and N_2O. PKS and CNS generally contain higher volatile and lower ash contents than coal. Nevertheless, they contain relatively high levels of alkali metals, such as potassium and chlorides (Lamberg et al., 2013). Different issues related to ash in combustion devices, like corrosion, bed agglomeration, slagging and fouling formation are linked with alkali substances, specifically sulphate and chlorides (Yang et al., 2016). At elevated temperatures, it is expected that potassium is typically released as gaseous K_2SO_4, KCl and KOH, which can condense and deposit on cooler surfaces within the boiler. Furthermore, the interaction between these potassium compounds and silicon can further lead to the formation of low-melting silicates, such as K_2SiO_3 and $K_2O \bullet 4SiO_2$ (Aho et al., 2010).

Pelletising of agro-wastes and wood is a technique of increasing the energy content and fuel efficiency through milling (uniform size), dehydration, mixing and conditioning of samples and binder to obtain homogeneous blend and densification through pellet mills. It was stressed that the agro-wastes have high percentage of K, Cl and N. It was deduced that a co-combustion of agro-waste pellet with solid hydrocarbon may give an improved outcome (Jeguirim & Khiari, 2022), (Cheah et al., 2022). Gehrig et al. (2019) investigated some mixtures of spruce and pellets of kaolin that were subjected to burning for over one and a half hours before stable equilibrium was achieved using a 12-kW boiler. Emission in the gaseous phase, the chemical composition of particulate matter as well as ash from boiler were obtained for the mixture. It was emphasised that kaolin additive reduced the potassium content of the particulate matter. Berdugo et al. (2020) measured the impacts of potassium metal on both hydrogen gas (H_2) and Carbon (II) Oxide (CO) when combusted at a temperature range of 845–1275 ^oC at 1.04 air ratio. They used potassium hydroxide, potassium, OH, hydrogen and Carbon (II) Oxide during the oxidation process. Inhibiting effect of potassium on H_2 and CO was affirmed.

Kuptz et al. (2022) conducted a study on the behavioural pattern of straw combustion and pellets. Quality of the fuel was improved by wood blending and kaolin additives. They emphasised that biomass fuel quality may meet ISO 17225-6 if the straw used in briquette is free from contamination and emission of the wood pellet is very low compared to that of Nitrogen Oxides (NO_x) emanated from biomass samples. However, a deposit of slag was recorded in biomass samples used which is a concern for low capacity boiler but the appropriate choice of additives would put the challenge under control.

Improving the combustion properties of lignocellulosic biomass can be achieved through pre-treatment methods, such as leaching with water or diluted acid, or through processes like torrefaction, which can reduce the corrosive and slagging tendencies of biomass, increase ash melting temperatures and alter particle formation during combustion process (Gudka et al., 2016). Recent studies have demonstrated that such pre-treatment can significantly affect the release of inorganic constituents and emissions during combustion. For instance, leaching has been shown to reduce the emission of harmful gases and shorten the combustion phase of biomass. Similarly, torrefied biomass has been found to reduce fuel segregation and lower emissions of Sulphur (IV) Oxide (SO_2) and Carbon (II) Oxide compared to raw biomass indicating its potential benefits in combustion systems.

Ravichandran & Corscadden (2014) attempted to reduce the particulate and gaseous emissions when water was used to leach the feedstock. Briquetting of water-leached and un-leached feedstock were produced and combusted. The finding showed that leaching of feedstock improves the fuel properties. It was reported that CO from leached feedstock (752 ppm) is about 50% lower than the un-leached feedstock (1584 ppm) and that co-combustor is required for briquettes made from herbaceous biomass. Furthermore, it was highlighted that the composition of fuel sulphur is not proportional to the SO_2. Although, it was noticed that there was a proportionality relationship that existed between Nitrogen Oxide (NO_x) emissions and the temperature of flue gas.

A study was conducted on the migration tendencies of Carbon (II) Oxide on additives, (K)Al-(Si) including K intermediate products. Combustion was conducted with 0.3 wt% of additive under 7.8 kW thermal source. The highest migration was obtained from kaolin in the emissions. In addition, it was observed that low thermodynamic K-Al-Oxides were adopted by K in a thin SiO_2 composition (Siegmund et al., 2024). Niu et al. (2019) simulated a rainfall to measure the effect impact of leaching on the straw of corn which is free of Cl, K and ash while the temperature of ash fusion was considered. Thus, the effect of leaching on the temperature of ash fusion with varying quantities of additives was analysed. It was stressed that the impact of the leaching duration is not pronounced when compared to leaching intensity and a decrease in K_2SO_4 and KCl were observed. This is due to the free of Cl and K_2O by leached biomass.

Furthermore, Kassman et al. (2010) investigated the combustion of torrefied willow in a bubbling fluidised-bed combustor. Low SO_2 emissions (measured with 6% O_2 concentration) during the process was observed. Despite these advancements, there has been no known reported research to the authors on the co-combustion of a torrefied PKS-CNS mixture with kaolin additives. This study aims to optimise the ash yield and Carbon (II) Oxide (CO) emissions during the combustion of torrefied palm kernel shells and cashew nut shells.

2.0 Materials and Methods

Collection and preparation of samples

Palm kernel and cashew nut shells were obtained from Olam Company (Nigeria) LTD, Ilorin, Nigeria (8.3994oN, 4.5985oE). Kaolin was selected as an additive for its capacity to mitigate ash buildup during the combustion process and it was sourced from a reputable local distributor. The kaolin additive was milled to a particle size of 0.05 microns. Biomass materials were placed in distinct airtight vessels for the torrefaction process (Oladosu et al., 2024). The torrefied PKS and CNS underwent proximate and ultimate analysis, with measurements conducted in triplicate using the E-871 ASTM standard. Bomb calorimeter (XRY-1-A) was used for Higher Heating Value (HHV) standard procedures.

Experimental procedures for torrefaction of PKS and CNS

A fixed bed pyrolytic apparatus was used for the torrefaction of the PKS and CNS. The experimental setup was designed and constructed locally for biomass torrefaction. Before the experiments, PKS and CNS were sun-dried for two weeks. For each experiment, the dried biomass was placed into the fixed-bed reactor and nitrogen gas was introduced into the furnace at a flow rate of 3 mL/min. This was done to maintain an inert atmosphere and prevent the combustion of both PKS and CNS (He et al., 2023). The torrefaction temperature of the biomasses was carried out at 250 °C and at a residence time of 30 min for both the PKS and CNS (Oladosu & Olawore, 2022).

Experimental design and evaluation of ash-generated and Carbon (II) Oxide emissions

The experimental setup involved the determination of ash produced and Carbon (II) Oxide emission through a systematic design. Six key parameters; quantity of TPKS, TCNS, KA, alongside temperature of the samples, residence time and particle size were chosen for the investigation. Utilising Optimal Combined Design within the Custom Design Methodology of Design-Expert software (13.0 version). A total of seventy (70) experimental runs were formulated. The assessment focused on two output parameters; ash yield and Carbon (II) Oxide emissions. The ash generated followed the methodology reported (Oladosu & Asafa, 2021). Samples of TPKS, TCNS and KA were placed in a tubular furnace and subjected to a specific heating temperature, residence time and particle size indicated in Table 1.

Table 1: Range of experimental parameters values

	TPKS (wt.%)	TCNS (wt.%)	KA (wt.%)	Temp (°C)	PS (mm)	Time (min)
Minimum value	50	15	0	700	1	60
Maximum value	70	35	15	900	3	120

Experimental runs and outcomes using optimal design

Figure 1 shows the profile of the 70 sequential experimental runs. It shows the percentage of the biomass mixture, PKS (L) and CNS (M) with additive (N). The operation temperature, particle size and time are captured in O, P and Q, respectively. Ash yield actual value, predicted value and residual are present in R, S and T, respectively. Whereas, the Carbon (*IV*) Oxide values for actual, predicted and residual are profiled in U, V and U, respectively.

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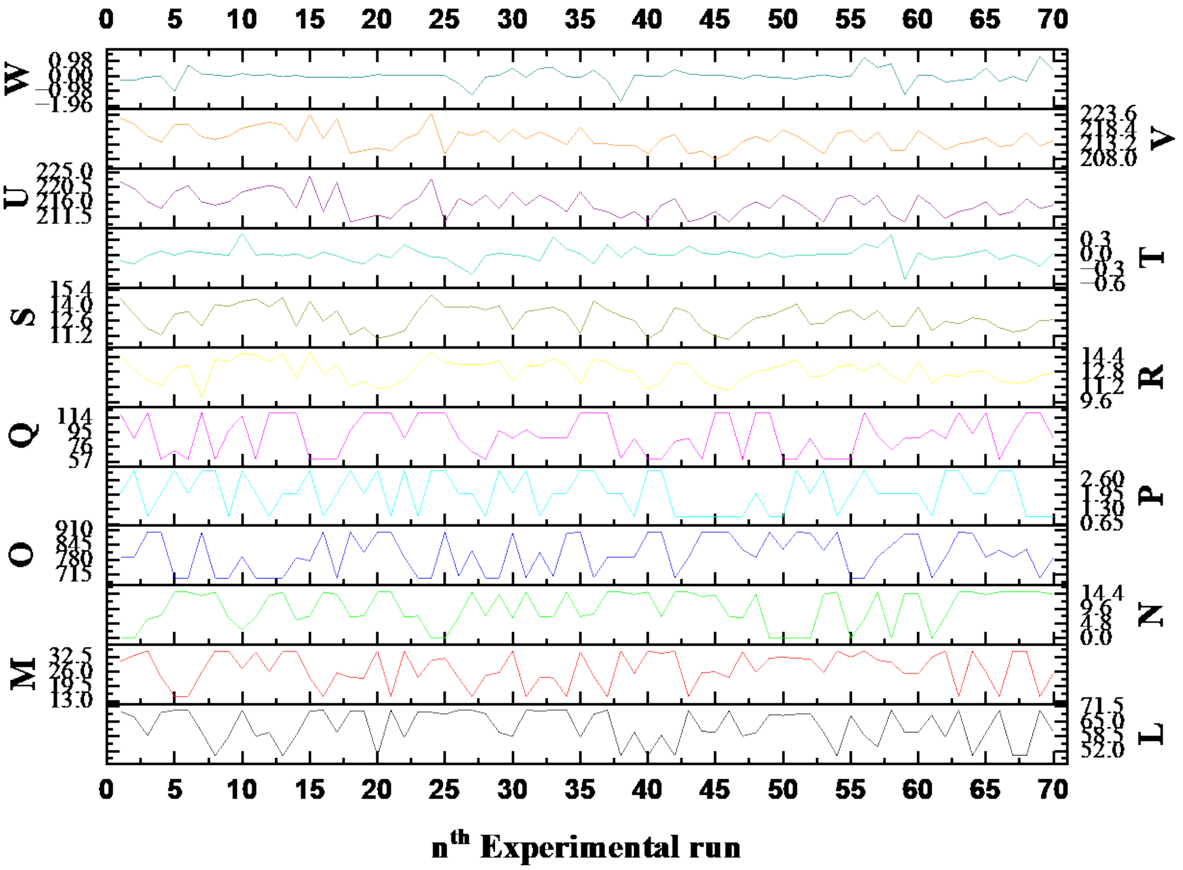

Figure 1: Experimental runs profile

Note the alphabets are used as notation in Figure 1 only: L–PKS(%), M–CNS(%), N–kaolin additive (%), O–temperature (°C), P–PS (mm), Q–time (s), R–actual ash yield, S–predicted ash value, T–residual ash value, U–actual CO, V–predicted CO and W–residual CO.

Numerical optimisation using the desirability function

The desirability approach is a widely utilised method that assigns a score to a set of responses and selects factor settings that maximise this score. This method combines multiple responses into a single dimensionless metric. Each response goal can vary, such as being within a specified range, minimised, maximised, or targeting a specific value, which defines the desirability function. This study focuses on minimising both ash yield and Carbon (II) Oxide emissions in the co-combustion of a torrefied PKS-CNS kaolin additive mixture. Equation 1 provides the desirability (d_i) for minimising both ash yield and Carbon (II) Oxide emission while the global desirability (D) is determined by the geometric mean of the desirability of individual response as stated in Equation 2 (Oladosu et al., 2023)

For minimisation

$d_i = 1$ when $Y_i < T_i$

$$d_i = \left(\frac{\text{High}_i - Y_i}{\text{High}_i - T_i}\right)^{wt_i} \tag{1}$$

when $T_i \leq Y_i < \text{High}_i$

$d_i = 0$, when $Y_i > \text{High}_i$

$$D = \left(\prod_{i=1}^{n} d_i\right)^{\frac{1}{n}} \tag{2}$$

where d_i is the desirability, $i = 1 \; to \; n$, Y is the response value, High and Low is the upper and lower limit of the response; T = target value of the response and wt = the weight with an assigned value of 1 and n= the number of responses.

3.0 Results and Discussion

Minimising ash yield and CO emissions in co-combustion of TPKS-TCNS with kaolin additive

The co-combustion of TPKS and TCNS with a kaolin additive, conducted at varying temperatures, particle sizes and residence times based on an optimal combined design, revealed (Table 1) that experimental Run 7 [PKS (60.50%), TCNS (25.6%), KA (13.9%)] at 900 °C, with a particle size of 3.00 mm and a residence

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time of 120 min and Run 46 [PKS (69.60%), TCNS (23.3%), KA (7.1%)] at 900 °C, with a particle size of 1.00 mm and a residence time of 120 min, produced the best outcomes. Run 7 exhibited the lowest ash yield (10.10%) and an average CO emission of 216 ppm, while Run 46 demonstrated an optimal balance with low ash yield (10.85%) and minimal emissions (210 ppm).

Conversely, Run 15 [TPKS (69.60%), TCNS (23.2%), KA (7.2%)] at 775 °C, with a particle size of 3.00 mm and a residence time of 60 min and Run 24 [PKS (69.1%), CNS (30.9%), KA (0.0%)] at 700 °C, with a particle size of 3.00 mm and a residence time of 120 min, yielded the least favourable results, with both exhibiting the highest ash yield of 14.9% and CO emissions of 223 ppm. To further assess performance, the higher heating value (HHV) of the selected runs was evaluated. Run 24 recorded the lowest HHV at 15.75 MJ/kg, while Run 46 achieved the highest HHV of 22.34 MJ/kg. The relatively lower HHVs of Run 7 (16.10 MJ/kg), Run 15 (15.98 MJ/kg) and Run 24 (15.75 MJ/kg) rendered these biomass samples inefficient, leading to lower thermal efficiency and increased air pollution during combustion.

Conclusively, Run 46 [PKS (69.60%), CNS (23.3%), KA (7.1%)] at 900 °C, with a particle size of 1.00 mm and a residence time of 120 min, provided the best overall performance. In contrast, Run 24 [TPKS (69.1%), TCNS (30.9%), KA (0.0%)] at 700 °C, with a particle size of 3.00 mm and a residence time of 120 min, was identified as the least effective.

Proximate and ultimate analysis

Proximate analysis was conducted on the TPKS and TCNS fuel samples. Table 2 revealed that TPKS has a moisture content, ash, fixed carbon and volatile matters and the ultimate analysis reflected 21.67 MJ/kg and 19.36 MJ/kg as calorific values for TPKS and TCNS, respectively. These findings agreed with a reported study, although insignificant variations are recorded (Oladosu et al., 2020). The variance could be due to differences in soil type, climatic conditions, or additives employed in the research.

Table 2: Proximate and ultimate analysis of TPKS and TCNS fuel samples

Fuel		**TPKS**	**TCNS**
Analysis	**Component**	**Composition (%)**	**Composition (%)**
Proximate	Moisture	5.40	7.20
	Ash	4.76	6.85
	Fixed carbon	23.87	22.14
	Volatile matter	65.97	63.76
Ultimate analysis	Carbon	50.46	47.73
	Oxygen	42.87	44.95
	Hydrogen	6.12	5.92
	Nitrogen	0.68	0.81
	Sulphur	0.03	0.02
	Calorific value	21.67 MJ/kg	19.36 MJ/kg

The significance of each coefficient was determined through probability (p) values and residual least square error analysis. Table 3 demonstrates that the quadratic models effectively captured the experimental data, as evidenced by $p < 0.01$ for both ash yield and CO emission. In the case of the ash yield model, R^2 and adjusted R^2 values stand at 0.9820 and 0.8643, respectively, whereas for CO emission, these values are 0.9820 and 0.8640. Based on the models, F values of 8.32 and 8.34 for ash yield and CO emission were computed with standard deviations of 0.4064 and 1.26, respectively.

In addition, these models exhibit significance at 99% confidence intervals, with a minimal chance (0.01%) of occurrence due to noise. Terms such as a mixture of TPKS and TCNS (AB), TPKS and kaolin (AC), TPKS, kaolin and temperature (ACD) and TCNS, kaolin and time (BCF) demonstrate significance at $p < 0.01$. This indicates there is a substantial impact on the rate of ash deposition during combustion. Furthermore, the lack of fit is deemed insignificant, which suggests that the model fits well with a low probability of error.

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Table 3: Proximate and ultimate analysis of TPKS and TCNS fuel samples

Source	Ash Yield					CO Emission				
	Sum of Square	Df	Mean Square	F-Value	p-value (Prob> F)	Sum of Square	Df	Mean Square	F-Value	p-value (Prob > F)
Model	81.08	59	7.628 x10^{-3}	30.42	< 0.0001 *	778.40	59	13.19	8.34	< 0.0001 *
Linear Mixture	8.36	2	0.055	219.17	< 0.0001*	67.43	2	33.71	21.31	<0.0001*
AB	0.6092	1	9.705 x10^{-3}	*38.71*	< 0.0001*	2.17	1	2.17	1.37	0.0083*
AC	0.7436	1	1.450 x10^{-3}	5.78	0.0202*	23.86	1	23.86	15.08	0.0211*
CD	1.53	1	5.601 x10^{-5}	0.22	0.6387	8.28	1	8.28	5.24	0.2718
CF	2.05	1	4.320 x10^{-4}	1.72	0.1957	15.01	1	15.01	9.49	0.7611
ACD	0.7724	1	1.414 x10^{-3}	5.64	0.0217*	11.25	1	11.25	7.11	0.7611
ACF	1.30	1	1.108 x10^{-4}	0.44	0.5095	17.55	1	17.55	11.09	0.3256
BCD	3.02	1	3.113 x10^{-7}	1.242 x10^{-3}	0.9720	12.71	1	12.71	8.03	0.8602
BCF	1.74	1	1.099 x10^{-3}	4.38	0.0417*	13.56	1	13.56	8.57	0.9593
BDF	0.6085	1	1.616 x10^{-4}	0.64	0.4260	6.80	1	6.80	4.30	0.4120
AD^2	1.794	1	1.794 x10^{-3}	7.15	0.0103*	0.3591	1	0.3591	0.2270	0.7404
BD^2	0.8944	1	1.343x10^{-3}	5.35	0.0251*	4.33	1	4.33	2.74	0.8486
BE^2	1.03	1	4.839 x10^{-4}	1.93	0.1713	12.30	1	12.30	7.78	0.7837
ABE^2	0.5557	1	8.608 x10^{-5}	0.34	0.5607	0.3417	1	0.3417.	00.216	4.4571
Residual	1.49	9	2.507 x10^{-4}			14.24	9	1.58		
Lack of fit	0.7717	4	2.705 x10^{-4}	0.034	0.3502**	7.24	4	1.81	1.29	0.3850**
Pure error	0.7150	5	2.301 x10^{-4}			7.00	5	1.40		
Cor Total	82.57	68				792.64	68			

*Significant at ($p<0.1$), ** Not significant

Formulation of optimal design models and statistical analysis

The models obtained to accurately predict ash and CO emissions, utilising TPKS, TCNS and kaolin mixture as coded factors generated by Optimal Design, are represented in Equation 3 and Equation 4, respectively.

$$\textbf{Ash yield} = -\,8.26\,AB\; -17.97\,AC\; +\; 7.83\,CD + 7.58\,CF - 10.93\,ACD - 10.67\ \mathrm{ACF} - 21.90\,BCD - 13.84\,BCF + 2.26\ \mathrm{BDF} - 5.44\,AD^2 + 3.86\,BD^2 - 4.28\,BE^2 + 7.80\,ABE^2 \tag{3}$$

$$\mathbf{CO}\ \boldsymbol{Emission} = -\,17.00\,AB\; -143.68\,AC\; +39.48\,CD + 61.49\,CF - 45.16\,ACD - 54.62\ \mathrm{ACF} - 129.53\,BCD - 150.84\ \mathrm{BCF} - 32.56\ \mathrm{BDF} + 4.19\,AD^2 + 11.47\,BD^2 - 17.98\,BE^2 + 6.29\ \mathrm{A}BE^2 \tag{4}$$

where, $A = TPKS$, $B = TCNS$, $C = Kaolin$, $D = Temperature$, $E = particle\ size$ and $F = Residence\ time$

Influence of kaolin additive on AY and CO emissions during combustion of TPKS and TCNS mixture

Figure 2 and Figure 3 illustrate the 3D response surface plots depicting ash yield and CO emission, respectively. This could be noticed as it has been influenced by variations in TPKS, TCNS, KA, combustion temperature, particle size and residence time. The ash yield exhibited a decreasing trend with higher combustion temperatures (Figure 2a) and increased proportions of TPKS at 7.1 wt% kaolin additive. For instance, at 793 °C, an ash yield of 14.8 wt% was observed, compared to 10.10 wt% at 900 °C. Similarly, extending the combustion duration from 60 min to 120 min resulted in a 31.8% reduction in ash yield while maintaining other parameters constant (Figure 2b). Furthermore, with 2.7 wt% kaolin and 69.6 wt% TPKS-TCNS fuel mixture, ash yield increased from 10.10 wt% to 14.8 wt% as the TPKS fraction increased from 57.7 to 70.0 wt% Figure 2c. Conversely, an increase in kaolin fraction up to 7.1% led to a substantial reduction in ash deposition (Figure 2c and Figure 2d). Maintaining other factors constant, an increase in kaolin content up to 7.10 wt% resulted in a significant decrease in ash yield from 14.80 wt% to 10.10 wt%.

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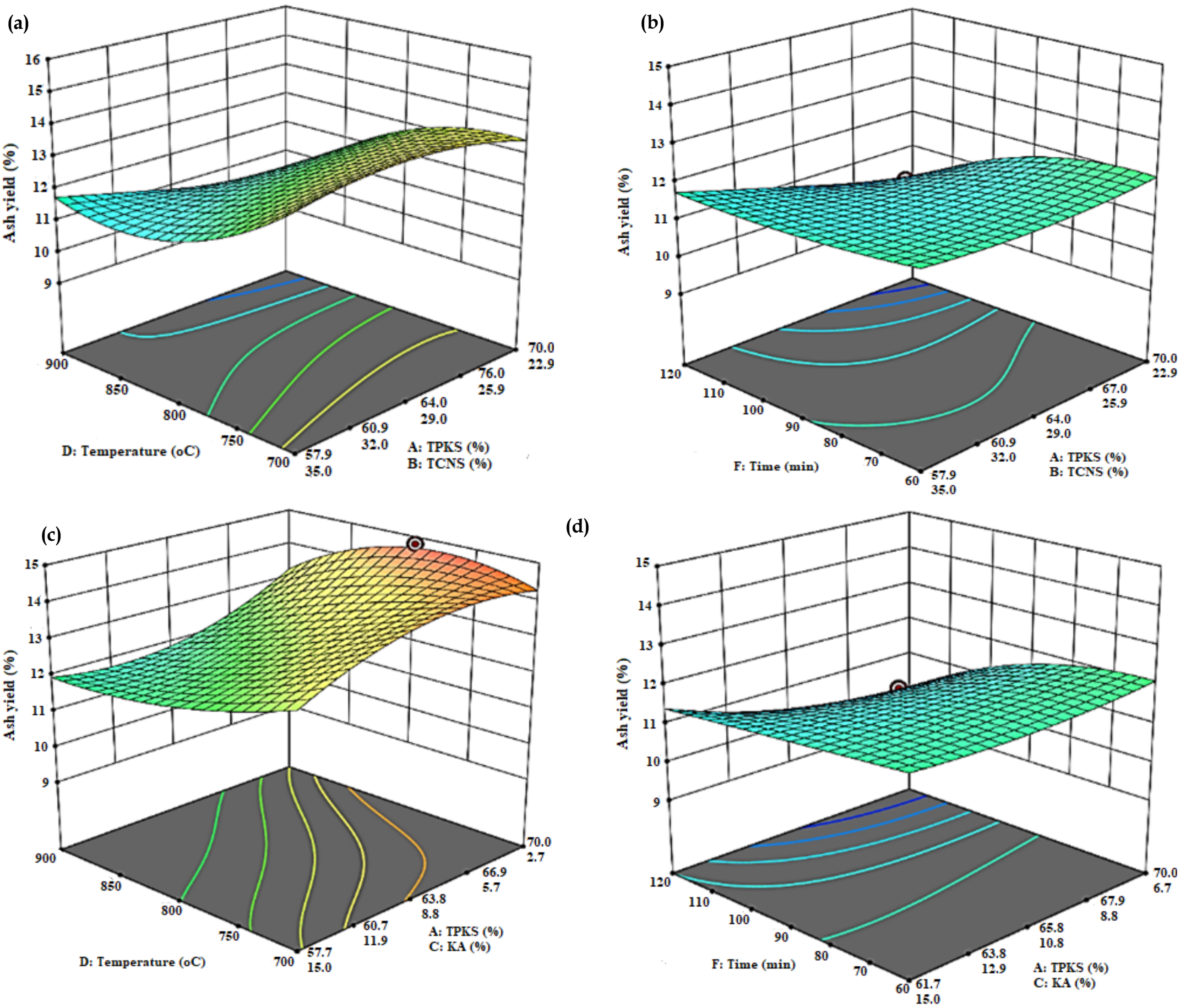

Figure 2: 3D-surface plot illustrating ash yield for TPKS, TCNS and KA fuel mixtures across varied temperatures and holding time

The impact of various factors including temperature, TPKS fraction, kaolin content and combustion duration on CO emissions is illustrated in Figure 3a – 3d. Analysis of Figure 3a reveals a significant decrease in CO emissions, from 221 ppm to 209 ppm, with an increase in combustion temperature from 700 °C to 900 °C, under conditions of 7.1 wt% kaolin and 70 wt% TPKS. Furthermore, an increase in the TPKS fraction from 57.9 wt% to 70 wt% resulted in a reduction in CO emissions to 221 ppm, while keeping kaolin content at 7.1 wt% and temperature at 900 °C.

Similarly, extending the combustion duration from 60 to 120 min led to a substantial decrease in CO emissions from 221 ppm to 209 ppm (Figure 3b), while maintaining a temperature of 900 °C and TPKS fraction of 70 wt%. Additionally, the influence of kaolin content on CO emissions is evident in Figure 3c and Figure 3d. At 900 °C and a combustion duration of 120 min, CO emissions decreased from 221 ppm to 209 ppm as the kaolin fraction increased to 7.1%. Likewise, after 120 min of combustion at 900 °C and a TPKS fraction of 70 wt%, CO emissions initially decreased from 221 ppm to 209 ppm as the kaolin fraction increased up to 7.1 wt%, followed by a subsequent rise in CO emission (Figure 3d).

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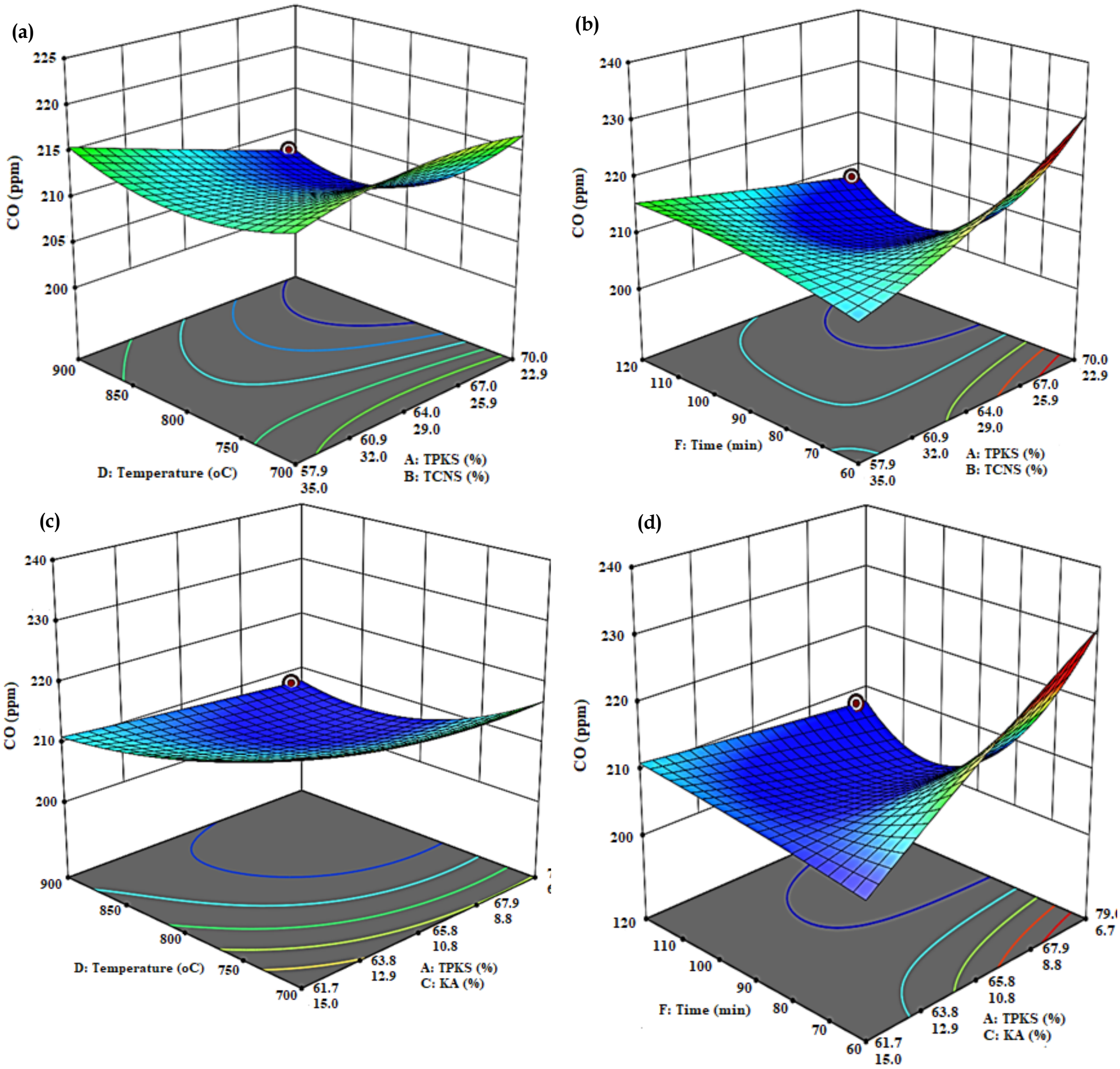

Figure 3: 3D-Surface plot depicting CO for TPKS, TCNS and KA fuel mixtures across varied temperatures and holding time

Furthermore, these findings affirm that higher combustion temperatures and longer residence times for combustibles promote more thorough combustion, leading to reduced ash deposition and CO emissions. Moreover, the ability of kaolin to elevate the melting temperature of the ash through dilution is noted, crucial in mitigating ash-related issues exacerbated by alkali metal content in biomass fuels, such as K and Na (Zhu et al., 2019). Many researchers (Garcia-maraver et al., 2014), (Fournel et al., 2015), (Lamberg et al., 2013), (Tzeng et al., 2015) reported that insufficient combustion, particularly prevalent in older boilers, can exacerbate pollutant formation. Effective duration within the combustion region and prudent utilisation of additives play crucial roles in attaining thorough combustion within a grate furnace. Previous studies have indicated that adding kaolin enhances nitrogen release rates during devolatilisation (Konsomboon et al., 2011). It is plausible that reductions in CO and ash are attributable to interactions between volatile compounds or elements released during biofuel decomposition and the surface area of the additive. These reaction regions could originate from the active components present in the additives.

Numerical Optimisation

The optimisation is based on the chosen desired goal ("in range" and "minimisation") for each input and response parameter. Table 4 presents the criteria for the optimisation to attain a minimum value of ash yield. The default weight value of ("1") was assigned to each goal to adjust the shape of certain desirability functions. The importance value of ("3") was selected to allow equal importance to all goals. Table 4 shows the numerical optimisation for the input and response parameters. The fuel mixtures of torrefied palm kernel shells (69.60 wt%), torrefied cashew nut shells having 23.30 wt.%, with kaolin additive, 7.1 wt.%, temperature at 900 °C,

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particle size of 1.00 mm and time at 120 min are considered for optimum quality of the ash yield and CO emission.

Table 4: Criteria of Optimisation

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: TPKS	in range	50	70	1	1	3
B: TCNS	in range	15	35	1	1	3
C: KA	in range	0	15	1	1	3
D: Temperature	in range	700	900	1	1	3
E: particle size	in range	1	3	1	1	3
F: Time	in range	60	120	1	1	3
Ash Content	minimise	10.1	14.9	1	1	3
CO (ppm)	none	210	222	1	1	3

Validation

The confirmation test was carried out at an optimal value of TPKS (69.60 wt.%), TCNS (23.30 wt.%), KA (7.1 wt.%), at the temperature of 900 °C, the particle size of 1.00 mm and residence time at 120 min. The percentage errors of the selected solution are within the tolerance and confirm the accuracy of the prediction model (Table 5).

Table 5: Confirmation test results for TPKS-TCNS biomass

Number	PKS %	CNS %	KA %	Temp °C	PS mm	Time min	Ash Yield %	CO ppm
Selected 1	**70.00**	**22.87**	**7.12**	**900.00**	**1.24**	**120.00**	**10.15**	**210.4**
2	67.91	25.15	6.92	898.12	1.38	118.05	11.02	212.2
3	67.83	25.44	6.71	897.48	1.93	112.94	11.17	213.4
Confirmation test	**70.00**	**22.87**	**7.12**	**900.00**	**1.24**	**120.00**	**10.36**	**209.8**
Error (%)	-	-	-	-			-2.06	0.28

XRD analysis

XRD spectrums of ash from a mixture of TPKS and TCNS, with and without kaolin additive of particle size 1 mm at 550 °C and at an elevated temperature of 900 °C are presented in Figures. 4a, 4b and 4c. The main crystalline phases detected at the mixed ratio of TPKS (50%); TCNS (50%) and KA (0%) for a temperature of 500 °C include graphite (C), sylvite (KCl), osumilite (K-Na-Ca-Mg-Fe-Al-S) and quartz (SiO_2). As the TPKS fraction increases up to 70% and at 30% of TCNS without the presence of kaolin additive and temperature of 900 °C, the diffraction intensities of C and SiO_2 increase gradually and K-Na-Ca-Mg-Fe-Al-S decrease. Figure 4(a-b). At the optimal process parameter (Figure 1), with TPKS (70%); TCNS (23%) and KA (7%) at an elevated temperature of 900 °C, the amount of (C) and (K-Na-Ca-Mg-Fe-Al-S) decrease gradually and SiO_2 increase significantly Figure 4c.

It is worth mentioning that the peak for KCl vanished with the inclusion of the kaolin additive. The presence of SiO_2 in the ash confirms the decreased extent of the reaction between K salts and chlorides (Liu et al., 2022). SiO_2 in co-combustion ash plays a major role in improving slagging and fouling behaviour as it can react with other compounds to form high melting point compounds and increase ash fusion temperature (Johansen et al., 2011). KCl gives rise to the formation of other problematic species as the temperature increases (Broström et al., 2007). Furthermore, Wang et al. (2012) stated that co-combustion with additives during the combustion process through the mechanism of chemical binding is a preferred strategy for mitigating ash-related issues and CO emissions, effectively capturing and transforming KCl into high-temperature melting compounds.

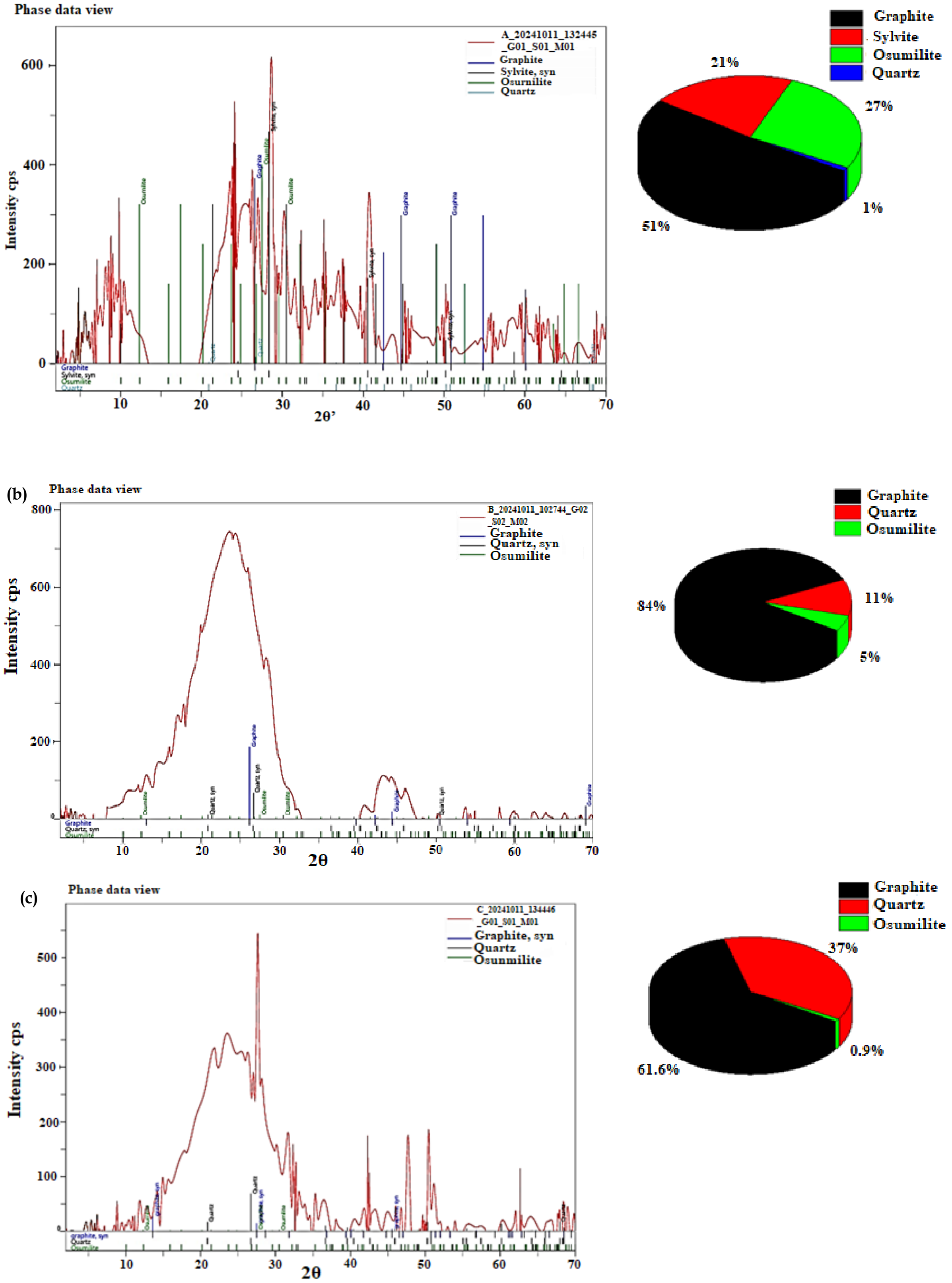

Figure 4: XRD spectra of ash resulting from a mixture comprising (a) 50% TPKS, 50% TCNS and 0% KA at 500°C. (b) 70% TPKS, 30% TCNS and 0% KA at 900°C. (c) 70% TPKS, 23% TCNS and 7% KA at 900°C

4.0 Conclusion

Optimal design was explored to investigate the influence of kaolin additive on ash yield and CO emission in the co-combustion of torrefied PKS and CNS in a furnace. Optimisation of kaolin additive, TPKS, TCNS and heating temperature significantly reduced the ash deposition and CO emission from 14.9% to 10.10% and 221 ppm to 209 ppm, respectively. The optimal composition achieved for the process was TPKS (69.6%), TCNS (23.3%), KA (7.1%,) and 900ºC, 1.00 mm, 120 min for temperature, particle size and residence time, respectively. The mathematical models developed for ash yield and CO emission using Optimal Design demonstrate a strong fit, with a coefficient of determination (R^2) value of 0.9820 observed for both responses. These refined models hold promise for application in thermal power plants aimed at reducing ash yield and achieving minimal Carbon (*II*) Oxide emissions.

Declarations

Authors declare that they have no conflicts of interest.

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