Effect of segun leaves blending on combustion behaviour of Indian washery reject coal

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Abstract

Experimental studies were carried out to analyse the combustion behaviour of segun leaves (SG), reject coal (RC) and their blends. RC of average relative density 2.1 was obtained by sink float test in the laboratory. Matured SG were collected from the plantation area of the IIT (ISM) campus of Dhanbad region and prepared in the laboratory as a blend with RC for further combustion experiments. SG and RC were characterised by proximate analysis, ultimate analysis and GCV. Combustion experiments were carried out with two different blending ratios of SG and RC in TGA to observe the effect of the blend on their combustion performance. Different combustion parameters such as T_i (Temperature of ignition), T_p (peak temperature), T_f (Temperature of burnout), rate of combustion, index of ignition, index of burnout, index of combustion performance, index of rate intensity, were estimated to determine the best blending ratios of SG-RC. Combustion results showed that when 10% by mass of SG is added to 90% mass of RC, the combustion performance of the blends improves. Ignition temperature reduces from 417^0C to 415^0C, peak temperature from 498 ^{0}C to 490^0C, burnout temperature from 565 ^{0}C to 563^0C and peak combustion rate from 2.89 weight%/minute to 2.95 weight%/minute. Analysis of combustion efficiency infers that blending SG with RC improves the combustion conversion of RC at higher temperatures (500˚C. Experimental analysis shows that a blend ratio of 10:90 (SG: RC) can be used in place of only RC to reduce the fuel cost in utilities.

Keywords: Plant RC; Segun leaves; TGA-DTG; Co-combustion; Combustion efficiency

1. Introduction

In India with the rise in demand for electricity, coal mining sectors are facing inherent problems in producing good quality coal for power generation. Indian coal is of drift origin and generation and accumulation of "washery RC" is a problem typical for India which averages about 50-60% of ash and 2200-2500 kcal/kg in Gross Calorific Value [1]. As a result, the emission level of SPM, carbon (CO_2) and nitrogen (NOx) in India on an individual power plant basis is higher than that in the industrialized "West". This is particularly true for carbon emissions. It is estimated that hardly about 10-15% of the thermal coal produced in India is cleaned with ash content of <34%, most commonly at 30-32% ash level for supply to the utilities. Besides clean coal, the other product obtained is a discard, commonly known as RC. Since the limit is <34% ash, considering the variability of Run of Mine (ROM) coal, process inefficiencies etc all the coal cleaning plants (washeries) practise safe clean coal ash of 30-32% for their linked supply to the utilities [2]. As a result, 10-15% of combustibles, sometimes more are lost as so-called "washery reject coal". Since the "washery reject coal" contains a considerable number of combustibles, a parallel economy in an unorganized sector, with no revenue to the state or union has emerged sometimes leading to law-and-order problems. To overcome the wastage of a large amount of "RCs" some PSU has set up Fluidized Bed Combustion plants to burn the "washery RCs". But there appear to be some loopholes for the lack of progress in this segment of the power sector. These include relatively low temperature attained in the burner, high abrasive ness of the "washery reject coal", poor combustion efficiency and emission issues. On a parallel front to address the climate change concerns associated with conventional fossil fuel burning, the development and utilization of biomass and biomass-coal blends as an alternative fuel for power generation are being promoted by the government. Biomass types include forest waste such as leaves, agricultural waste as well as municipal waste. However, the burning characteristics of biomass, coal and biomass-coal mixture could be different as the combustion process largely depends upon the diffusion of O_2 and CO_2 gases to coal particles and the presence of mineral matters are the main pockets of resistance in the path of diffusion. As a result, the combustion behaviour of high ash low GCV "washery RCs" and low ash high GCV biomass (like rice husk, wheat, wood, bark, branches and leaves etc.) are expected to be different. De et al., 2009 [3] in their study, have discussed the economic feasibility of retrofitting for biomass cofiring. They have found that with a higher percentage of biomass cofiring with coal, a greater reduction in CO2 emissions can be achieved but with an increase in total and specific costs. Overall electricity generation cost was increased due to the additional cost of biomass cofiring. Rathnam et al., 2013 [4] discussed in detail the biomass and coal-co-firing prospects in India and indicated that it could be carried out on a commercial scale. They suggested utilization of appropriate technologies, cost compensation by earning carbon credits, better establishment of the biomass sector and subsidies from the government to support the industry are required to implement cofiring technology in Indian coal-based power plants successfully. Seepana et al., 2017 [5] studied the feasibility of pelletized wood cofiring with high ash Indian coals in a pilot-scale burning test facility. They reported that NO and SO_2 concentrations decreased by up to 8% and 16%, respectively, with the increase in pelletized wood proportion in coal. A significant reduction in CO_2 emission was observed with an increase in biomass percentage in the coal blend. Aich et al., 2019 [6] studied the effect of sal leaves blending with reject coal and observed significant improvement in their combustion behaviours. In the Indian context, the majority of Northeastern states are endowed with rich forest sources. Other major states also have good agricultural residues such as rich straw, rice husk, wheat straw, etc., as unused biomass. Overall, agricultural and forest waste make up most of India's biomass-based energy sources. The conflict between food and fuel can be avoided by using agricultural and forestry waste in existing power plants. In this context, the present work investigates the effect of SG and RC blending on the combustion behaviour of RC. The results of this study are expected to provide pathways for the proper utilization of two waste fuel sources, namely RC and SG for effective utilization in combustion applications.

2. Experimental procedures

Matured fallen SG of around 25 kg was collected from the plantation area of the IIT (ISM) campus in Dhanbad. Subsequently, leaves were prepared in the laboratory following the standard procedures and were made ready for laboratory analysis. 350 kg of Run of Mine coal was collected from the Jharia coalfield in (Jharkhand, India). A typical RC of an average relative density of 2.1 g/cm^3 was prepared in the laboratory by sink-float test. A blend of 100 gm segun leaves-RC was prepared in three different mass ratios 10:90, 20:80, and 30:70 using a laboratory blender. Representative samples were considered for further characterization tests. Proximate analysis, ultimate analysis and GCV were carried out to determine the physicochemical characteristics of SG and RC. All the experiments were repeated twice, and the average data was reported in the table. Combustion studies of RC, SG and their different blends were performed in a thermo-gravimetric unit at a heating rate of 10˚C/minute. Based on TGA-DTG data different combustion-related parameters such as ignition index (P_i), burnout index (P_f) and heat intensity index (P_h) were determined as given in equation (1-4) [7-9].

$$P_i = \frac{DTG_{max}}{t_p \times t_i} \quad (1)$$

$$P_f = \frac{DTG_{max}}{\overset{\Delta}{\rightarrow} t_{1/2} \times t_p \times t_i} \quad (2)$$

$$T_f = \frac{DTG_{max} \times DTG_{mean}}{T_i 2\ T_f} \quad (3)$$

$$P_h = T_p \times n\left(\frac{\Delta t_{1/2}}{DTG_{max}}\right) \quad (4)$$

3. Results and discussions

3.1 Characterization of SG and RC

From Table 1, it is seen that RC has the highest ash of 62% compared to SG (14%). Sa uch higher percentage makes the fuel difficult to combust due to the formation of a thick ash layer during combustion progression. However, SG has a higher VM of 65% compared to RC (10%). Overall combustible content of SG is higher compared to RC which makes the fuel better for combustion performance. The presence of higher VM makes the fuel easily ignitable while higher FC helps the fuel to achieve a stable combustion performance. Higher combustible in SG contributes to higher GCV in fuel. Table 2 shows the ultimate analysis results of RC and SG on as received basis. From Table 2, it can be noted that SG has the highest carbon content of 42% compared to RC (29%). Similarly, the hydrogen content of SG is higher than RC. Sulphur of both fuels lies below the permissible limit for internationally traded fuels.

Table 1: Proximate analysis of RC, SG on as received basis

Fuel	Ash (%)	Moisture (%)	VM (%)	FC (%)	GCV (Kcal/Kg)
RC	62.00	1.10	10.00	27.20	2341
SG	14.00	7.40	65.40	13.30	5500

Table 2: Elemental analysis of SG and RC on as received basis

Fuel	C (%)	H (%)	N (%)	S (%)	O (%)
RC	29.20	1.47	0.59	0.35	5.29
SG	42.20	6.00	1.40	0.30	28.70

3.2. Combustion studies of RC, SG and their blends

The combustion behaviour of SG, RC and their blends was carried out in a TGA analyser, and the obtained results are shown in Figure 1a. Further mass loss rates with respect to temperature profile are shown in Figure 1b. From Figure 1a, it can be seen that from temperature 50˚C to 150˚C, there is a certain mass loss observed which is ascribed to moisture evaporation from the fuel surface. After 150˚C, there is weight noted inferred adsorption of O_2 gas on the porous surface [8,9]. After 417˚C for RC and 235˚C for SG, rapid mass loss starts indicating the initiation of the devolatilization process. This mass loss increases further during the initiation of the char combustion process. For RC and SG, the following temperatures are 498˚C and 301˚C.

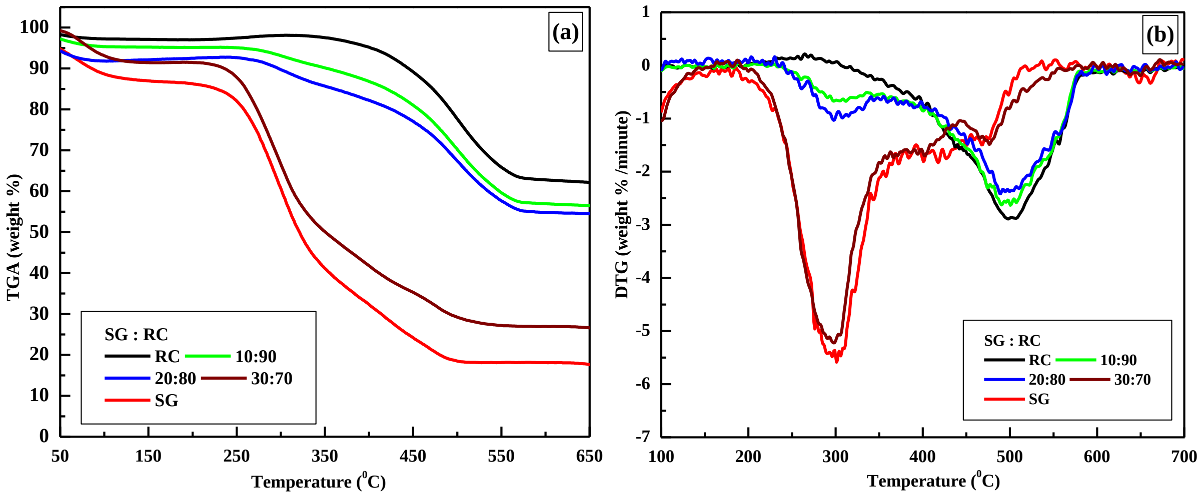

Figure 1: a) TGA of SG-RC and their blends, b) DTG of SG-RC and their blends.

Table 3: Burning profile temperature of individual and blended fuels.

Fuel	T_i, °C	T_p, °C	T_f, °C	**(DTG_{max}) weight %/minute**
RC	417	498	565	2.89
SG	235	301, 358	485	5.58, 2.09
SG: RC				
10:90	415	494	563	2.63
20:80	297	298, 488	554	1.01, 2.41
30:70	293	294, 468	542	1.11, 1.87

After 565°C for RC and 485°C for SG, the TGA curve becomes constant indicating the end of combustion with residual ash left as the end product. Detailed analysis of the mass loss rate with respect to temperature is shown in Figure 1b. Table 3 shows the burning characteristics temperature of SG, RS and their blends. From Table 3 it is observed that the ignition temperature (T_i) for SG is 235°C whereas for RC it is 417°C. On addition of 10% by mass of SG T_i decreases to 415°C and with further addition of 30% by mass T_i decreases to 293°C. Similarly, peak temperature (T_p) for SG is 301°C with a corresponding DTG_{max} of 5.58 weight%/min whereas for RC T_p is 498°C (DTG_{max} 2.89 weight%/minute). Multiple Tp is observed at 301°C and 358°C for SG. First peak at temperature 301 was due to the decomposition of hemicellulose and cellulose while the second peak at 358 was due to combustion of residual lignin and FC [7,9]. For blends, it is observed that the addition of SG, lowers the burning profile temperature (T_i, T_p and T_f) of the blends. This decrease in temperature is due to the additional effect of SG with RC and due to higher combustibles in SG which helps to achieve superior combustion performance for blends. Thus, the blend of SG in suitable proportion with RC enhances the combustion property of the blended fuel.

3.3 Effects of blends on combustion performance and comprehensive indices

Different combustion indices such as P_i (weight % per min^3), P_f (weight % per min^4), T_f (weight %^{2} per min^2 C^3), P_h (°C) are calculated to get detailed understanding of the combustion behaviour the fuel blends during combustion process. Variations of P_i, P_f, T_f and P_f with different blend ratios are of SG-RC are shown in Table 4.

From Table 4 it is seen that with an increase in mass of SG in blends from 10% to 30% P_i increases from 2.07 to 4.67 2wt % per min^3, P_f increases from 4.66 to 5.92 wt % per min^4, T_f increases from 1.63 to 5.84 weight%^{2} per minute^2 C^3 and P_h decreases from 1.31˚C to 0.63˚C. Higher value of P_i, P_f and T_f for SG signifies that the combustion performance of SG is better than RC due to presence of higher lignocellulosic compounds and higher porosity in SG [6,7]. A lower value of P_h infers a better heat release rate for SG compared to RC [8]. Overall, combustion indices infer that SG having good combustion characteristics compared to the poor performance of RC and hence blending SG with RC improves the combustion performance of RC.

Table 4: Combustion performance indices of segun leaves, RC coal and their blends

Fuels	$P_i(\text{x } 10^{-3})$	$P_f \text{x } 10^{-5}$	$T_f(\times\ 10^{-7})$	P_h (⁰C)
RC	1.65	4.13	1.56	1.31
SG	10.3	47.0	22.9	0.41
SG: RC				
10:90	2.07	4.66	1.63	1.31
20:80	4.45	5.28	3.50	0.66
30:70	4.67	5.92	5.84	0.63

3.4 Effect of coal blending on combustion efficiency

Combustion efficiency plays a vital role in determining the effective utilization of RC-SG blended fuel in boiler utilities. Combustion efficiency was calculated from TGA-DTG data and using the following equation (5) [6]:

Percent combusted of total combustible $ή = \frac{W_{110} - W_T}{W_{110} - W_{TC}}$ x 100 % (5)

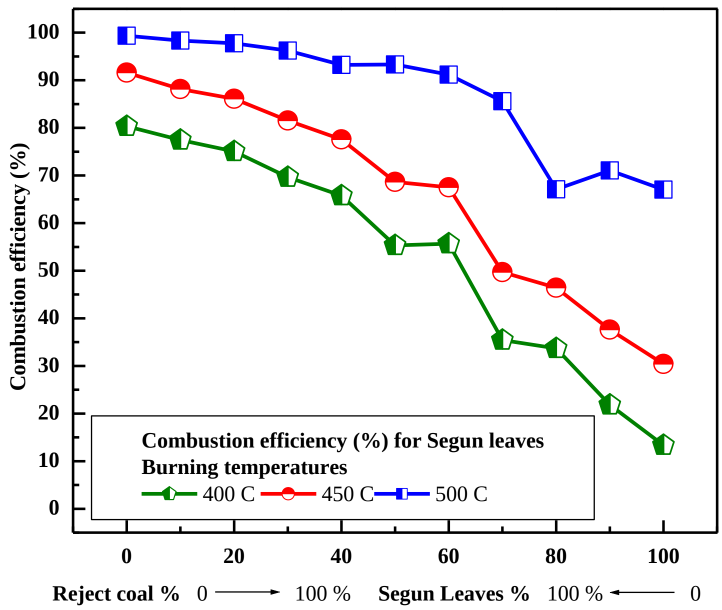

Figure 2: Variation of combustion efficiency of RC-SG and their different blend ratios at various temperatures of 400˚C, 450˚C and 500˚C.

Variations of combustion efficiency at three different temperatures of 400˚C, 450˚C and 550˚C for SG-RC blends are shown in Figure 2. From Figure 2, it can be seen that combustion efficiency is higher for blended fuels compared to individual fuels. At 100% SG, combustion efficiency at three different temperatures is 13%, 30% and 67%. With the addition of 10% SG combustion efficiency increases to 21%, 37%, and 72% and with further addition of 20% SG there are abrupt increases in combustion efficiency to 34%, 46% and 88%. Therefore, from the above analysis, it is inferred that the addition of SG improves the combustion efficiency of RC. Thus, an increase in combustion efficiency with an increase in mass of SG in the blend is due to higher combustibles present in SG which enhances the burning performance of the blended fuel and hence improves the overall combustion efficiency of the fuel in the boiler [6,7]. The addition of 10% SG in blend with RC improves the combustion efficiency significantly, therefore 10%SG blending with 90% RC can be considered as the optimum blending ratio.

3.5 Analysis of activation energy of the individual and blended fuels

The activation energy (E) and pre-exponential factor (s^{-1}) for SG, RC and their blends were estimated using the reaction of first-order Arrhenius law of the Coats-Redfern method as follows [6,8]:

$$\frac{d\alpha}{dt} = A\exp\left\{-\frac{E}{RT}\right\}.f(\alpha) \quad (5)$$

$$\ln\frac{g(\alpha)}{T^2} = \ln\left(\frac{AR}{\beta E}\right) - \frac{E}{RT} \quad (6)$$

By plotting the appropriate left-hand side of the below equations versus 1/T or ($\ln\frac{g(\alpha)}{T^2}$ vs. $\left(\frac{1}{T}\right)$). The slope equals E/2.303 R and from there the value of E and A can be calculated from the above equations. Where, α is the extent of conversion, expressed as $\alpha = \frac{(m_0 - m_t)}{(m_0 - m_\infty)}$ and $f(\alpha) = (1-\alpha)^n$. ***f (α)*** is the hypothetical model of the reaction mechanism; n is the order of reaction, *A* is the frequency factor (min^{-1}); E (kJ/mole) is the Activation Energy; R= 8.314 kJ/mol, universal gas constant, T is the absolute temperature; m_0 is the initial mass of the sample; m_t is the mass of the sample at time t; m_∞ is the final mass of the sample [6,8].

Table 5: Activation energy and pre-exponential factor of SG, RC and their blends.

Fuel	**E (kJ/mol)**	**Pre-exponential factor (A, s^{-1}) × 10^{-5}**
RC	78.79	0.03
Segun leaves	25.54	0.79
SG: RC		
10:90	55.95	0.05
20:80	23.39	0.06
30:70	22.41	0.25

Table 5 shows that the E of RC and SG are 70.90 kJ/mol and 8.62 KJ/mol respectively. The lower value of E infers faster and more rapid reaction between O_2 gas molecules and combustibles that initiates a faster combustion process. On the other hand, it is observed that the addition of 10% by mass of SG to RC E reduces to 42.40 KJ/mol from 70.90 kJ/mol. With the further addition of SG in the blend by 20% E reduces to 23.39 kJ/mol. A decrease in E could be possibly due to the additional effect of SG which contains a higher content of volatile combustibles that releases the required amount of heat energy required for optimum combustion performance.

4. Conclusions

The present work investigates the effect of SG blending on the combustion behaviour of Indian washery reject coal. Overall characterization study infers that SG has the highest GCV (5500 kcal/kg) compared to RC. Also, SG contains a higher VM (65.4%) compared to RC (10.0). Analysis of burning profile parameters infers that SG has superior combustion properties compared to RC and hence lower burning profile temperatures are achieved. With the addition of 10%, SG in blend with RC T_i reduces from 417˚C to 415˚C, T_p from 498˚C to 494˚C and T_f from 565˚C to 563˚C. Analysis of combustion performance indices shows that P_i, P_f, and T_f increase from 2.07 weight % per min^3, 4.66 weight % per min^4, and 1.63 weight $\%^2$ per min^2 C^3 to 4.67 weight % per min^3, 5.92 weight % per min^4, and 5.84 weight $\%^2$ per min^2 C^3 when SG quantity was increased from 10% to 30%. Increase in P_i shows better ignition performance while higher P_f and T_f show better burnout and combustion performance. The heat intensity index (Ph) reduces from 1.31 (°C) to 0.63 (°C) when SG was increased from 10% to 30%. Activation energy reduces from 78 kJ/mol for RC to 56 kJ/mol when 10% SG is added to the blend. Analysis of combustion efficiency at different temperatures of 400˚C, 450˚C and 500˚C proves blending SG significantly improves the reject coal combustion performance. Overall current work implies that the addition of SG with RC improves the GCV as well as combustion performance of the blends significantly.

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