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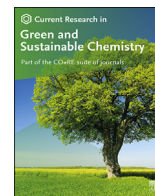
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Study of low-rank high sulfur coal fine with biomass

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ABSTRACT

Efficient combustion is important for the energetic recovery of coals. In the present study, thermogravimetric analysis (TGA) has been employed to obtain valuable information on the combustion characteristics of low-rank coal fine waste and acacia as biomass. Combustion profile indicates that acacia is helpful, for better ignition and burnout characteristics of coal due to the better reactivity and enhanced release of volatiles at lower temperature. The incorporation of acacia into the coal during combustion, decreases the ignition temperature and hence, yields a better combustion performance. Negligible amounts of ash and sulfur in the acacia sample, in comparison to the low-rank coal fines, are highly beneficial in order to reduce the emission of harmful sulfurous gases and particulate matters into the atmosphere. Statistical tools, such as Correlation Coefficient and Principal Component Analysis (PCA), have confirmed that blending low-rank coal fine waste with acacia biomass is highly beneficial for better ignition and efficient combustion.

1. Introduction

The total combustion of low-rank coals is a major issue that can result in improper burning and hence, the formation of bottom ash with unburned carbon, which can eventually increase the operational cost [1]. Incomplete char burnout is closely associated with the premature extinction of char particles, which is caused by a combination of phenomena, such as: sintering, thermal annealing and unstable combustion modes [1–3]. Moreover, any increase in the quantity of incomplete combustion products can render the resulting ash, unsuitable for other applications (e.g. cement production). For the enhancement of combustion efficiency, several works have been carried out on the coal burning process and catalytic combustion [4–10]. Combustion performance of low-rank coals can be increased by adding catalytic materials, such as MnO₂, which will enhance the amount of volatiles released and hence the coals can be combusted at lower temperature [11]. However, the use of

catalyst will enhance the combustion performance of coal and it will in turn increase the amount of ash formed during coal combustion. Secondly, the use of catalysts will not help in reducing the amount of SO₂ released into the atmosphere.

However, the combustion performance can also be increased by using materials which can release more volatiles at low temperatures. Biomass is one of the alternatives that are sustainable and green in nature [12–14]. Biomass as a fuel, includes: wood, agricultural residues, forest residues and energy crops and globally, and it represents the fourth largest energy source with high reactivity and volatility [15]. These properties support the ease of production of biomass-derived fuels and value-added chemicals. Biomass has many advantages, which include: easy storage, high burning efficiency, low pollution, low dust and high heating value. Co-firing of biomass with coal reduces SO₂ emission since biomass contains negligible amount of sulfur [16–18]. As a result of the renewable nature of biomass [19],

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there is a possibility of declination of CO₂ emission with the increase of biomass blending ratios.

Moreover, it is reported that the combustion of biomass alone led to technical problems, which include corrosion and fouling on hot surfaces [20]. The ash deposition and fouling problems on hot surfaces can be reduced by burning coal/biomass blends [21]. Due to high volatility, biomass blending with coals can affect the entire combustion profile and the operation efficiencies. Co-firing of coal with biomass will be a beneficial step, towards a greener and cleaner environment. By considering the environmental problems created by the use of coals as fossil fuel and in order to increase the use of renewable resources, biomass is considered as an alternative for the enhancement of combustion efficiency of coals. Hence, it is important to investigate the combustion characteristics, such as: ignition, burnout performance etc. of less valued (low-rank) high sulfur Indian coals, blended with locally available biomass along with their raw samples.

However, coal fines as one of the coal mining wastes is a serious problem of the coal industry, which is traditionally dumped in a cone-shaped heap. This waste has the potential to pollute the air, water and soil. Utilization of such waste for the energy recovery can not only solve the problem of the industry, but also can generate revenue. In the present study, an attempt has been made to increase the combustion performance and to reduce the amount of sulfur and the ash content present in high sulfur low-rank North East Indian coal by blending them with biomass as additive. The biomass, Acacia, was chosen for this investigation since it is abundantly available in the NE region of India. Although, the bark of acacia is used for medicinal purpose in Nagaland [22], the wood becomes waste, other than as fire wood. Hence, it can be considered to be suitable for use with coal fines in order to benefit and ameliorate its combustion behavior and the consequent environmental impacts.

2. Experimental setup

2.1. Materials and methods

The coal sample was obtained from Tuensang Coalbelt (latitude 26°14'-26°25'N and longitude 94°51'-95°04'E) of Konya, Nagaland. The woody biomass (acacia) sample was collected from the South West of Jorhat City (25°49' and 27°17' N latitude and 93°18' and 95°26' E longitude) of the North East Region (NER) of India. The coal (K) and biomass (A) samples were air-dried and were grinded to between 0.198 and 0.211 mm size and then they were mixed in five different biomass/coal ratios (1:4, 1:2, 1:1, 2:1 & 4:1).

The proximate analysis of the raw and blended samples was carried out on a TGA/DTG analyzer (TGA 701, Leco, USA) by using the standard methods [23,24]. The carbon, hydrogen and nitrogen contents were estimated by using the 'Elemental Analyser' (Model: PerkinElmer 2400). The total sulphur was determined by the 'Sulfur Analyser' (Leco Corporation, USA) [25], whereas oxygen was estimated by difference. The calorific values were determined by using a bomb calorimeter (Make: LECO, AC 350 LECO model) [26].

The thermal degradation of all the coal/biomass blends and the raw coal and woody biomass were carried out on a TGA/DTG analyzer (TGA 701, Leco, USA) from ambient temperature (30 °C) to the terminal temperature of 900 °C. The experiments were conducted non-isothermally at a heating rate of 20 °C/min by using between 0.5 and 0.9 g of the raw and the blended samples (biomass/coal ratios 1:4, 1:2, 1:1, 2:1 & 4:1) prepared, under oxygen atmosphere. The purity of oxygen used was 99.995% with a 5 ppm nitrogen, 0.5 ppm CO₂, 0.5 ppm CO, 0.9 ppm moisture and 0.2 ppm THC as impurities. The weight loss (TG signals) and the rate of weight loss (DTG signals) were recorded as a function of time and temperature. TG-DTG experiments were also performed under nitrogen atmosphere by following the same heating method. The purity of nitrogen used was 99.9995% with 2 ppm oxygen, 0.3 ppm CO₂, 0.05 ppm CO, 2 ppm moisture, 0.1 ppm THC and 0.01 ppm total VOC as impurities. The combustion parameters, such as: ignition temperature

(T_e), ignition index (D_i) and burnout index (D_f), were calculated according to the methods discussed elsewhere [11,27].

2.2. Determination of the ignition temperature (T_e), ignition index (D_i) and burnout index (D_f)

(a) Ignition temperature

Ignition temperatures for all coal-biomass blends and their raw samples were determined from the TG measurements performed in air and nitrogen atmospheres. It can be noted that there was more than one meeting point of both combustions (oxygen atmosphere) and pyrolysis (nitrogen atmosphere) in the curves during the heating process. However, only the first meeting point is considered as the ignition temperature from which, the combustion of the fuel begins [27]. A typical example for the determination of the ignition temperature is shown in Fig. 1. The plots for the determination of ignition temperature for each material can be found in the supplementary material.

(b) Ignition index (D_i)

Ignition index (D_i) is determined from the following equation [28]:

$$D_i = (dw/dt)_{\max} / t_p t_e$$

where (dw/dt)_{max} is the maximum combustion rate, t_p is the corresponding time of the maximum combustion rate and t_e is the ignition time.

(c) Burnout index (D_f)

The burnout index is used to evaluate the burnout performance, which can be described as follows [28]:

$$D_f = (dw/dt)_{\max} / \Delta t_{1/2} t_f$$

where, Δt_{1/2} is the time zone of (dw/dt)/(dw/dt)_{max} = 1/2 and t_f is the burnout time.

3. Results and discussion

3.1. Physico-chemical analysis

The chemical analysis of biomass/coal in the blends along with raw coal (Konya) and woody biomass (acacia) was carried out and the resulting data are shown in Table 1. From the proximate analysis, it was observed that the biomass/coal ratio 1:4 has low moisture, low volatile

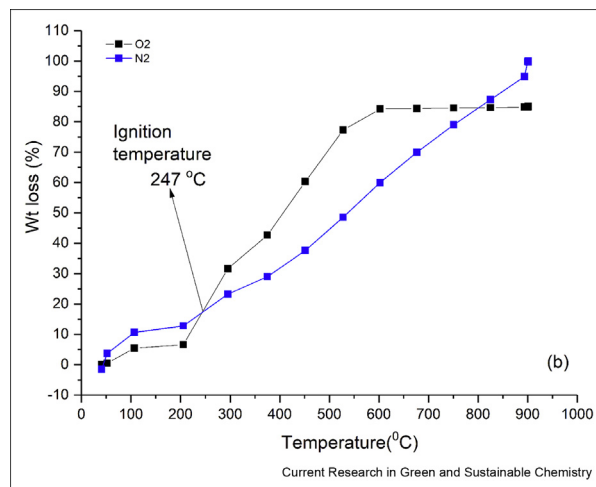


Fig. 1. Ignition temperature of acacia-coal blend (A/K:4/1).

Table 1

Chemical analysis of coal, biomass and its blend (wt %).

Fuel description	A	Acacia-Coal blend ratio					K
		A/K(4:1)	A/K(2:1)	A/K(1:1)	A/K(1:2)	A/K(1:4)	
Proximate analysis (as received)							
M	11.26	10.25	9.25	7.54	6.19	5.13	4.33
VM	75.79	64.04	58.6	49.69	43.59	38.73	32.8
Ash	0.65	5.61	8.17	12.51	15.96	18.5	22.28
FC	12.3	20.1	23.98	30.26	34.26	37.64	40.59
VM/(VM+FC)	0.86	0.76	0.71	0.62	0.56	0.51	0.45
Ultimate analysis (as received)							
C	37.5	44.3	48.9	49.0	51.1	52.2	56.7
H	6.71	6.53	5.79	5.55	5.47	5.21	5.03
N	0.58	0.82	0.93	1.11	1.23	1.33	1.44
S	0.06	1.05	2.18	2.59	3.49	3.61	5.32
O	55.2	47.3	42.2	41.8	38.7	37.7	31.5
Calorific Value (cal/g)	4570	4445	4735	4975	5280	5465	5985

Note: A = Acacia, K = Konya.

matter (VM) and high fixed carbon in comparison to other ratios and raw acacia, while the 4:1 ratio has high VM, low ash, high moisture and low fixed carbon in comparison to other ratios and the raw coal. The results indicate the fact that with increasing coal ratio, fixed carbon also increases and hence, the calorific value of the blends increases, while the reverse is the case with increasing the wood content in the blends. The ash content of biomass was found to be significantly lesser (0.65%) in comparison to the raw coal (22.28%). The analysis showed that an increase in the coal percentage in the blends, results in a rise in the overall ash percentage, which is obvious. Ultimate analysis showed that the C content is highest in the acacia/coal ratio 1:4, followed by 1:2 and 1:1. The C content in the blends and particularly in the 1:4 ratio is almost equivalent to that of a raw coal (Konya), which is due to the higher percentage of carbon in the coal. In the Acacia/Konya blend, the carbon percentage ranges from 44.3 to 52.2% and for hydrogen from 6.53 to 5.21%. Thus, for gasification purposes, coal with higher biomass content

in the blend will be suitable for a better hydrogen yield. Although there is a significant drop in the carbon content with the increase in biomass ratio, the calorific value is comparatively higher for the coal-biomass blends, which is due to the increased hydrogen content when compared to the raw coal (Table 1). The second reason for the higher calorific value of the coal-biomass blend can also be assumed to be due to the low ash content in the biomass. More importantly, the sulfur in the NER coal, which needs to be reduced, is a major threat for its utilization. Table 1 shows that sulfur content of the coal is high (5.32%), whereas that in the biomass is negligible (0.06%). For coal-biomass blend, the sulfur value is found to be lowest for sample A+K (4:1), followed by the 2:1 and 1:1 ratios. Moreover, the coal sample contains low amount of volatile matters and hence, low volatile fuel ratio (VM/(VM+FC)), which increases with the increasing ratio of the acacia blended with the coal. The higher values of the volatile matters and volatile fuel ratio are essential for the ignition of the fuel. Furthermore, acacia contains greater

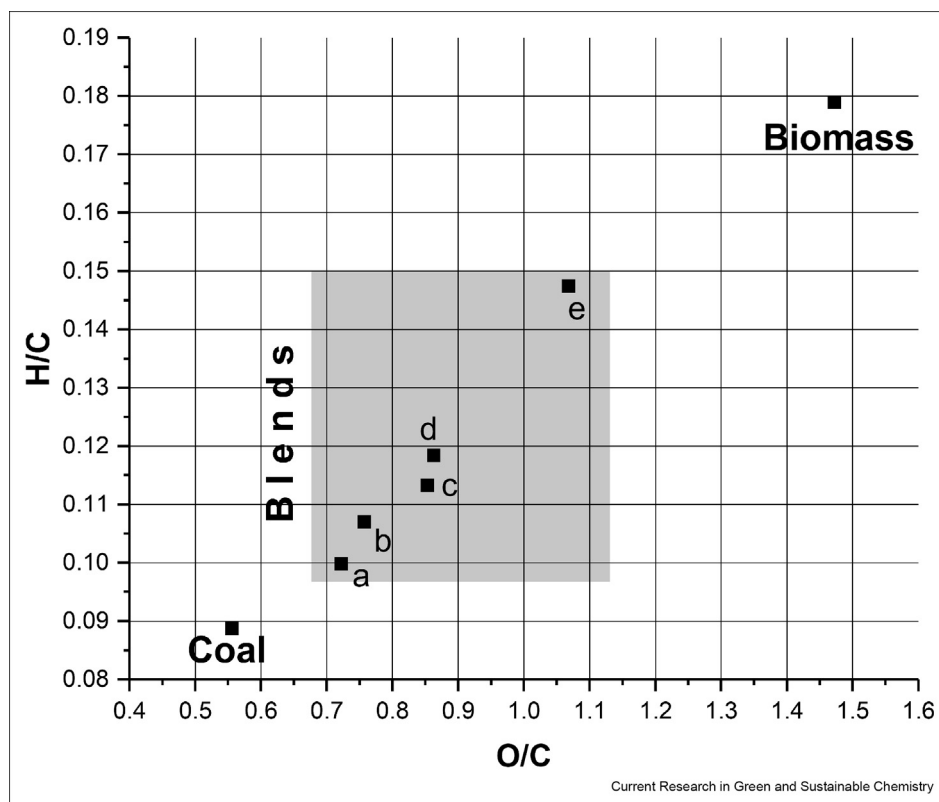


Fig. 2. Van Krevelen diagram of coal, biomass (Acacia) and their blends (Coal: Biomass ratio, a = 4:1, b = 2:1, c = 1:1, d = 1:2, e = 1:4).

amount of oxygen when compared to the raw coal (Konya), which helps in the ease of ignition and hence, completes the combustion of the coal (Table 1). Therefore, it is considered that blending coal with acacia with greater amount of volatile matter and oxygen content, will enhance the combustion efficiency.

The oxidation elements, such as: carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulfur (S), contribute to the oxidation/combustion process of the fuels. The Van Krevelen diagram (Fig. 2), derived from the elemental analysis of fuels, is a practical means of studying their reactivity [29,30]. The high O/C and H/C values indicate better reactivity and hence acacia is more reactive than coal and as a result, it easily gets oxidized/combusted. The reactivity of the blended samples lies in

between the coal and acacia. The coal-acacia blend (e = 1:4) is found to be more reactive among all the blended samples because of the higher amount of acacia in the blended sample. The better the reactivity, the better will be the ignition and subsequently, combustion and gasification.

Acacia has higher oxygen and hydrogen contents and lesser carbon than coal. This is the reason why acacia has lower heating value when compared to the coal. However, blending acacia with coal shows increased carbon content and hence, high heating value. The main reason behind the lower heating value of acacia is due to the lower energy contained in the carbon-oxygen and carbon-hydrogen bonds than in carbon-carbon bonds [30]. Interestingly, coal-acacia blend (e = 1:4) shows a resemblance with raw acacia, whereas blends (a = 4:1, b = 2:1, c

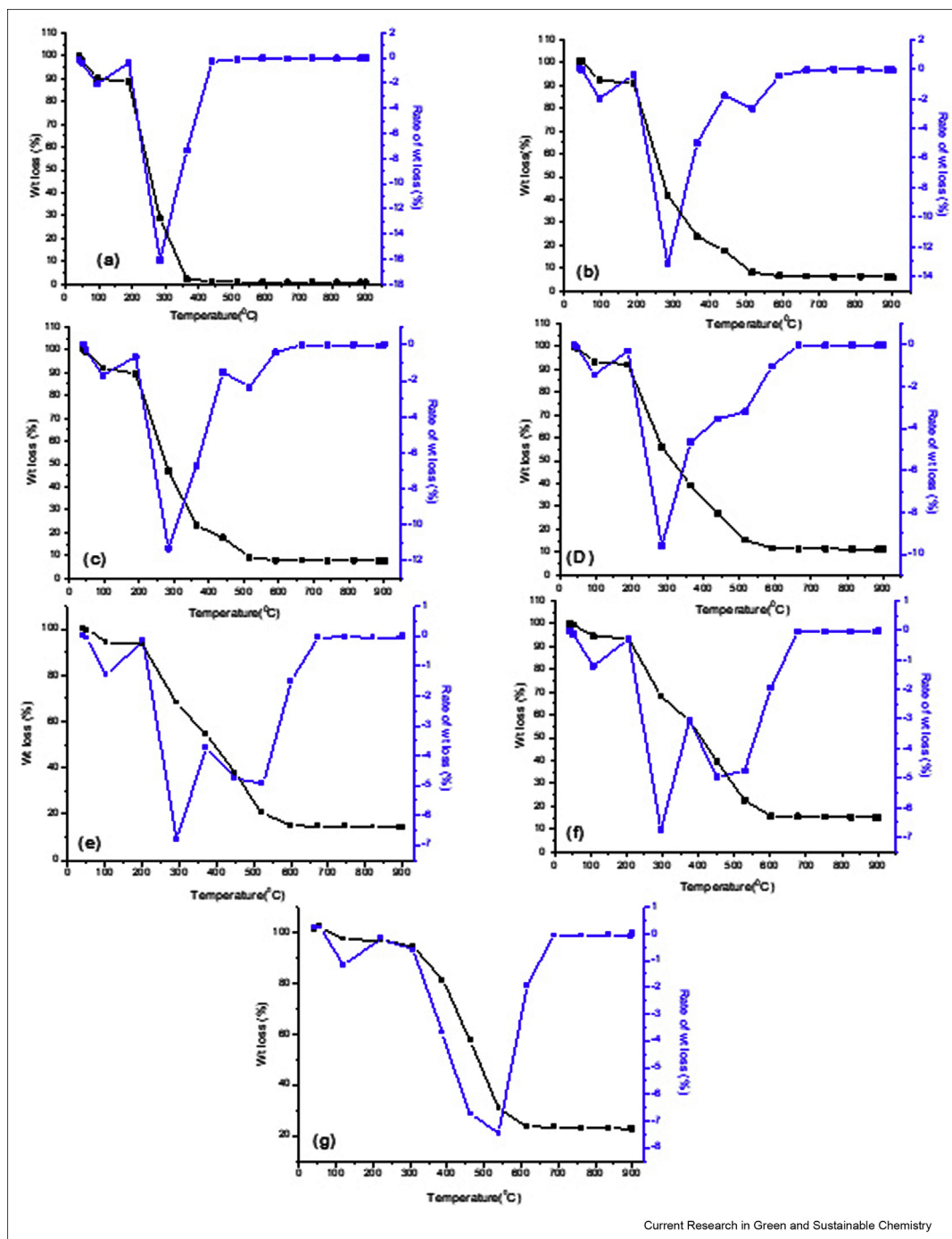


Fig. 3. TG-DTG profiles of blended and raw samples (a) Acacia (A); (b) A+K(4:1); (c) A+K(2:1); (d) A+K(1:1); (e) A+K(1:2); (f) A+K(1:4); (g) Konya (K).

= 1:1 and d = 1:2) are close to raw coal (Fig. 2) and hence, their heating values are comparable with the raw coal. Moreover, due to the lower ash and sulfur contents and the higher oxygen and hydrogen contents, coal-acacia blends can be used for combustion purpose, which will suppress harmful emissions and other particulate matters and at the same time, such blends will yield better reactivity that is needed for total combustion.

3.2. Combustion profile of low-rank coal fine, acacia and their blends

Total combustion is essential for the utilization of solid fuels, e.g. coal. Ma et al. [11], observed that catalysts, e.g., MnO₂, could enhance the combustion efficiency of coal. In order to increase the use of renewable resources as well as to secure sustainable development, biomass is an alternative to the catalyst. Blending coal with biomass can not only increase the combustion efficiency of coal, but also reduce the dependency on fossil fuel and the attendant emission of harmful sulfurous gases. Following the incorporation of acacia as a model biomass into coal, two peaks are observed at around 300 °C and 500 °C (Fig. 3 (b-f)), instead of only one peak at around 300 °C (Fig. 3a) and 500 °C (Fig. 3g) in the case of raw biomass and coal, respectively. The first peak appearing at the lower temperature, represents the volatiles present in the fuel, whereas the second peak represents the more complex organic structures, which decompose at higher temperature [11]. The first peak is responsible for the ease of combustion of the fuel, whereas the second peak helps to increase the combustion time [31]. There is an additional peak in both the coal and acacia samples. This peak is due to the removal of the moisture present in the samples and does not contribute in the combustion process. Moisture removal started from 50 °C and it is completed at around 200 °C. The weight lost, due to moisture, volatiles, fixed carbon, and ash residues were estimated from the TGA profile and it is found to be similar with the proximate analysis (Table 2).

The combustion profiles for the raw coal and acacia appear to be simple. It shows one peak for the removal of moisture and another peak for the combustion of hydrocarbons. However, the second peak indicates the fact that the raw coal and acacia are ignited due to the release of the volatiles at a certain temperature. The acacia sample contains greater amount of volatile matters (~75%) and its de-volatilization occurs at lower temperature when compared to coal, hence, the acacia sample gets ignited at lower temperature (Fig. 3a). Moreover, due to the greater amount of volatiles present in the acacia, it produced sufficient amount of energy, which helped to burn the fixed carbon present in the sample and hence only one peak, is observed, for the volatiles and the fixed carbon. However, in the case of coal, the amount of volatiles present is only ~32% and de-volatilization occurred at higher temperature (Fig. 3g) when compared to the raw acacia. This is due to the complex organic nature of coal and hence, the ignition of raw coal started at higher temperature. In addition, in the case of raw coal, only one peak is observed, which is due to the fact that once the volatile matter present in the coal gets ignited, the higher ignition temperature helped to ignite the more complex fixed carbon. On the other hand, the addition of acacia to coal, shows two peaks: one for the volatiles and other for the more complex fixed carbon. This is due to the fact that acacia gets de-

Table 2
Calculative proximate parameters of coal, acacia and its blends as per different temperature ranges.

Samples	M (%)	VM + FC (%)	Ash (%)
A	11.37 (41.9–190 °C)	87.68 (190–439 °C)	0.95
A+K(4:1)	10.39 (41.92–190 °C)	83.55 (190–590 °C)	6.06
A+K(2:1)	9.04 (50.76–190 °C)	82.77 (190–591 °C)	8.19
A+K(1:1)	7.88 (50.76–190 °C)	80.41 (190–593 °C)	11.71
A+K(1:2)	6.56 (50.76–199.6 °C)	78.52 (202–673 °C)	14.92
A+K(1:4)	6.32 (52.75–206 °C)	77.87 (206–676 °C)	15.81
K	3.25 (58.35–222 °C)	73.88 (222–689 °C)	22.87

Values in the parenthesis indicate the range of temperatures.

volatilized and gets ignited at lower temperature than coal, whereas coal contains more complex fixed carbon, which needs higher temperature than acacia to be ignited and hence the two separate peaks are observed.

3.3. Ignition performance of low-rank coal and acacia blends

The TG and DTG profiles of low grade-high sulfur Indian coal (Konya) and biomass (acacia) blends, along with their raw samples under oxygen atmosphere are presented in Fig. 3 (a-g). The characteristic combustion parameters from the burning profiles are calculated and are shown in Table 3. The ignition temperature (T_e) for the coal is found 336 °C, which gradually decreased with the addition of acacia content and found to be minimum for the A+K(4:1) sample (Table 3). Furthermore, the ignition index (D_i) of the raw coal is found to be 18.77×10^{-3} , which also increased with increasing acacia content. Hence, D_i for the biomass-coal blended sample, A+K(4:1) is found to be maximum. A higher value of D_i indicates a preferable stoichiometric catalytic performance of the acacia, as additives to the ignition temperature of coal [32]. Hence, acacia shows its performance by decreasing the ignition temperature of coal and it is found to be minimum ($T_e = 247$ °C), corresponding to an ignition index, ($D_i = 77.68 \times 10^{-3}$) for the A+K (4:1) ratio. Moreover, it has been established that the higher the volatile matter, the easier will be the fuel to get ignited [31]. Therefore, it can be expected that the higher the acacia content in the coal, the lower will be the ignition temperature, which is due to the higher amount of the volatiles released from blends.

It has been established that metal oxides as catalysts (e.g. MnO₂) promote the decomposition and transformation reactions in coal, resulting in enhanced release of volatile matters and hence a decrease in the ignition temperature of the coal [11]. On the other hand, due to the greater content of volatile matter in the biomass, the fuel is easily ignited and its combustion goes to completion. Hence, the volatile matter released from the biomass is burnt at a low temperature and it releases enough energy to improve the ignition characteristics of the coal.

3.4. Burnout characteristics low rank coal fine and acacia blends

The burnout temperature (T_f) is identified from the TG/DTG curves. Burnout temperature (T_f) of the coal is found to be ~875.1 °C and this value decreased with increasing acacia ratio in the blend (Table 3). This is due to the early and rapid combustion of the volatile matter in the biomass. Moreover, the biomass contains greater amount of oxygen than the coal and acts as carrier of oxygen. It promotes the oxygen transfer to the char of the coal [11], which helps in the combustion of the coal. Hence, with increases in the acacia content, the burnout temperature decreases, which results in the increase in the burnout efficiency of the blended samples.

Furthermore, it is found that the burnout index (D_f) of the coal is 24.9×10^{-5} (Table 3). The burnout index also increased with the increasing amount of acacia in the blend, which is found to be maximum for the A+K (4:1) sample. As the burnout performance is directly proportional to the value of the burnout index, the A+K (4:1) blended sample showed higher burnout performance when compared to other blends. This is due to the rapid combustion of the volatile matter in acacia [31].

It is also indicated that the maximum combustion rate " $(dw/dt)_{max}$ " of coal is ~7.48% min⁻¹. This value gradually increased with the incorporation of acacia with the attendant decrease in the corresponding time of the maximum combustion rate (t_p) and temperature (T_p). The sample A+K (4:1), with highest amount of acacia, showing greatest combustion rate. Hence, it is revealed that acacia facilitated the combustion of the coal. Fig. 3 indicates the main peak for the coal, occurring between 284 and 662 °C with a maximum weight loss rate at 515 °C. These results are due to the thermal decomposition of the various components, such as: loss of volatiles, char gasification and the combustion of

Table 3
Characteristics parameters of co-combustion.

Samples	T_e (°C)	$(dw/dt)_{max}$ (% min ⁻¹)	t_e (min)	$\Delta t_{1/2}$ (min)	t_p (min)	T_p (°C)	t_f (min)	T_f (°C)	D_i ($\times 10^{-3}$)	D_f ($\times 10^{-5}$)
A	195	16.05	11.57	18.40	14.62	283.55	51.13	666.0	90.18	106.9
A+K(4:1)	247	13.14	11.61	18.75	14.97	288.05	53.90	755.4	77.68	90.6
A+K(2:1)	277	11.33	12.32	18.90	15.33	291.77	57.32	759.1	51.14	70.4
A+K(1:1)	286	9.60	14.8	19.15	15.7	295.37	58.40	817.2	49.63	53.7
A+K(1:2)	292	7.95	15.31	19.33	15.7	299.98	58.57	821.2	32.63	44.5
A+K(1:4)	298	7.73	15.52	19.45	15.72	303.70	58.57	835.9	31.66	43.4
K	336	7.48	15.53	19.48	26.03	540.13	61.16	875.1	18.77	24.9

Note: T_e = Ignition temperature, $(dw/dt)_{max}$ = maximum combustion rate, t_e = ignition time, t_p = time of maximum combustion rate, T_p = corresponding temperature of $(dw/dt)_{max}$, t_f = burn out time, T_f = burn out temperature, D_i = ignition index and D_f = burn out index.

the complex hydrocarbon and fixed carbons in the coal [32]. The corresponding temperature for the maximum weight loss, gradually decreased with increasing acacia blending ratio, which is due to the enhanced release of volatile matter and hence the maximum combustion rate is found to be $\sim 13.14\% \text{ min}^{-1}$ for sample A+K (4:1).

3.5. Statistical analysis of coal-biomass blends

Statistical parameters, such as the correlation coefficient and Principal Component Analysis (PCA) are applied to proximate analysis, calorific value and co-combustion parameters for the studied coal-biomass samples by using the SPSS16 software. The statistical analysis of the coal-biomass blends, show the interrelation between the proximate analysis, maximum combustion rate " $(dw/dt)_{max}$ ", ignition temperature " T_e ", ignition index " D_i ", burnout time " t_f ", burnout index " D_f " and calorific value "CV".

The Pearson correlations, derived for these sets of data (Table 4), show that the T_e has a strong positive correlation with ash ($r = 0.948$), FC ($r = 0.954$) and CV ($r = 0.850$), whereas strong negative correlations with M ($r = -0.915$) and VM ($r = -0.958$) exist. This indicates the fact that the ignition temperature of the samples, having high moisture and volatile contents, is easy to ignite due to the low initial moisture removal and the volatile releasing temperature [33] and hence, these result in a low calorific value. However, the high ash and FC contents increase the ignition temperature of the coal-biomass samples due to the difference in the distribution of heat and the ease with which the various forms of carbon ignite, respectively [34]. The D_i shows the reverse effect as shown by ignition temperature (T_e), since they show strong negative correlation ($r = -0.961$). The maximum combustion rate " $(dw/dt)_{max}$ ", shown by the coal-biomass blends have strong positive correlation with M ($r = 0.959$), VM ($r = 0.980$), D_i ($r = 0.974$) and D_f ($r = 0.978$) and strong negative correlation with Ash ($r = -0.967$), FC ($r = -0.985$) T_e ($r = -0.948$), t_f ($r = -0.958$) and CV ($r = -0.849$). This suggests that the maximum combustion rate are highest for the samples that have low ignition temperatures, which in turn lowered the time required for total combustion of the sample. This further led to the increase in the ignition and burnout indices, but decreased the calorific value. This effect can be

Table 4

Bivariate analysis of proximate, ignition temperature (T_e), ignition index (D_i), maximum rate of wt loss ((dw/dt)), burnout time (T_f) and burnout index (D_f) and calorific value (CV).

	M	VM	Ash	FC	CV	T_e	D_i	$(dw/dt)_{max}$	t_f	D_f
M	1.000									
VM	0.990	1.000								
Ash	-0.995	-0.998	1.000							
FC	-0.990	-0.999	0.995	1.000						
CV	-0.956	-0.925	0.947	0.916	1.000					
T_e	-0.915	-0.958	0.948	0.954	0.850	1.000				
D_i	0.964	0.976	-0.972	-0.975	-0.911	-0.961	1.000			
$(dw/dt)_{max}$	0.959	0.980	-0.967	-0.985	-0.849	-0.948	0.974	1.000		
t_f	-0.915	-0.952	0.941	0.952	0.847	0.988	-0.972	-0.958	1.000	
D_f	0.976	0.989	-0.985	-0.988	-0.920	-0.968	0.987	0.978	-0.978	1.000

The data which are less or higher than 1 are highlighted in bold.

seen in Tables 1 and 3, where the incorporation of biomass increased the ignition and burnout indices, but decreased the calorific value of the samples studied.

3.6. Principal component analysis (PCA)

The proximate analysis, maximum combustion rate " $(dw/dt)_{max}$ ", ignition temperature (T_e), ignition index (D_i), burnout time (t_f), burnout index (D_f) and calorific value of the coal-biomass blends were selected for the PCA, due to their continuity of measurements in time scale. For a better interpretation, the components with an Eigen value of <1 , are eliminated so that fewer components are dealt with [35]. From Table 5, it is observed that only one component can be extracted, while the other components are eliminated. When the percentage of the total variance of the extracted component is accumulated, it can be seen that the principal component accounts for $\sim 96.14\%$ of the total variance of the original data (Table 5). The variables having loadings more than 0.5, are only considered [36], in order to explain each factor (Table 6). Factor 1 accounts for 96.140% of the total variance in the variables observed and this is positively associated with: M, VM, D_i , $(dw/dt)_{max}$ and D_f and negatively associated with ash, FC, T_e , t_f and CV. The high loading of VM, indicates that its increase in the coal-biomass blending samples, decreases the FC content along with the reduction in the time required for burning out of the samples studied. The reduction of FC, leads to the decrease of CV, which is negatively associated with VM. The association of the maximum combustion rate (positively) and burnout time (negatively) with VM, indicates that a good burnout efficiency of the blends, can be obtained by increasing the burnout index of the samples studied.

Table 5

Eigen values and % variability by principal components.

	F1	F2	F3	F4	F5	F6
Eigen value	9.614	0.244	0.092	0.036	0.013	0.002
% Variance	96.14	2.437	0.922	0.357	0.126	0.018
Cumulative %	96.14	98.577	99.499	99.856	99.982	100

Table 6
Principal component analysis.

	F1
M	0.985
VM	0.996
Ash	-0.994
FC	-0.995
CV	-0.930
Te	-0.968
Di	0.989
(dw/dt) _{max}	0.980
t _r	-0.969
D _r	0.997

The ignition temperature is negatively associated with VM and positively associated with ash and FC, which indicate the fact that the potential of igniting the coal-biomass blends requires less time for samples that have high volatile, low ash and FC. These results show increases in the ignition and burnout indices and a decrease in the calorific value with the incorporation of biomass with high VM content when compared to the coal sample (Tables 1 and 3).

4. Conclusion

From the present investigation, it has been found that the co-combustion of acacia with high sulfur–low ranked coal is beneficial for the control release of SO₂ and NO_x into the atmosphere. Due to the low content of ash and sulfur in the biomass, blended samples will lead to low emission of harmful sulfurous gases and particulate matters (PM). From the combustion performance of the blended samples, it has been found that with the addition of biomass, the ignition and burnout performance of the coal are improved, which can be attributed to the decreases in the ignition and burnout temperatures. Hence, the sample with the greatest content of acacia, i.e., A+K (4:1) shows the best ignition and burnout performances. The maximum combustion rate of the blends increased with increases in the blending ratio of acacia, while the corresponding temperature (T_p) and time (t_p) decreased. Due to the high volatile matter content of acacia, the incorporation of acacia resulted in the change of the overall volatile matter content in the blends. The study also reveals that co-combustion of high sulfur–low grade coal with acacia or other biomass waste or energy-crop derived biomass, is favourable for not only reducing greenhouse gas emission, but also the highly desirable low cost fuel options in energy recovery.

Credit Author Statement

U N Gupta conceived the presented research idea, supervised the research activities and wrote the manuscript. B Mahanta and A Saikia have carried out the experiments, characterization and optimization studies. P Saikia, B K Saikia, J Jayaramudu and E R Sadiku provided critical opinion and helped to shape research work. S Periyar Selvam verified the analytical methods. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The all authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.crgsc.2020.100023>.

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