Chapter 4

Combustion characteristics of Bambusa *tulda* and petroleum coke blends

4.0 Introduction

Petroleum coke, commonly known as petcoke, is a solid by-product generated during petroleum refining. It is a residual waste material characterized by high carbon content, a high calorific value, and low ash content. Due to globalization and economic development, there has been a significant increase in crude oil processing at refineries, which has led to a increase in petcoke production worldwide [139]. Petcoke is often used as a substitute for coal in power plants and various manufacturing industries, such as cement, steel, and textiles. However, because of its higher carbon content, petcoke combustion releases more carbon dioxide than coal and other pollutants that contribute to air pollution and greenhouse gas emissions. Additionally, depending on its source, petcoke also contains high levels of sulphur, leading to further air pollution and acid rain. Despite its environmental impact, industries continue to use petcoke in their combustion processes[1] because it is readily available and more affordable than other alternatives [155]. However, one of the main challenges with petcoke is its low reactivity, making it difficult to use as a fuel source or convert it into value-added products. Petcoke is often co-fired with more reactive fuels with high volatile matter content, such as biomass, to utilize efficiently. In India, 47 thermal power plants have begun using agro-residue-based biomass pellets for co-combustion with coal. The Ministry of Power, Government of India has mandated that 5% of biomass be incorporated into the co-firing process in thermal power plants in India starting from the fiscal year 2024-25, with an

---

[1] *https://powermin.gov.in/sites/default/files/Revised_Biomass_Policy_dtd_08102021.pdf*

This chapter published in
Bora, A. and Mahapatra, S. Experimental study on combustion characteristics of bambusa tulda and petcoke at varying blending ratios. **Energy,** 320, 135383, 2025.

increase to 7% by 2025-26[1]. Co-firing biomass with petcoke in an appropriate blend ratio for boilers, furnaces, and similar applications presents a promising solution for reducing greenhouse gas emissions. This approach decreases pollution, generates reliable energy, and enhances combustion reactivity [100].

Numerous studies have analysed the combustion behavior of coal, petcoke, and biomass. A crucial factor that influences the combustion characteristics and operational performance is the composition of the ash residues produced during combustion. However, relying solely on these factors may not fully explain the combustion and flame behavior of blends of petcoke and biomass. Therefore, conducting a comprehensive experimental study and analysis of the single-particle combustion of petcoke and biomass blends is essential. Only a few studies have investigated the single-particle combustion behavior of blended fuel particles comprising biomass and petcoke. In India, various types of biomass are available as fuel sources. This study focuses on Bambusa *tulda* (B. *tulda*), a type of bamboo widely available in Northeast India. It is a popular fuel source due to its high productivity and short growth cycle [50]. This research aims to investigate the effects of different blend ratios of B. *tulda* and petcoke, as well as variations in particle size, surface area-to-volume ratio, mass degradation, combustion behavior, and the characteristics of ash residues. This study seeks to enhance the understanding of the combustion behavior of blended fuel samples of petcoke and biomass.

4.1 Results and discussion

4.1.1 Flame behaviour study

A study is conducted on a biomass fuel sample (B. *tulda*), of spherical shape, to investigate the behavior of flames during single-particle combustion in the presence of air. Upon heating, a flame appeared on the surface of the fuel, indicating the start of combustion. Sequential images are captured 60 seconds after ignition once the flame had fully engulfed the sample, as shown in Fig. 4.1. Volatile combustion stage began when a visible flame appeared on the surface of the fuel particle, signifying the ignition of volatile gases. It ended when the flame gradually diminished and faded as the volatile matter is consumed. The presence of bright, luminous flames characterized this phase. Char combustion stage commenced when the flame is entirely extinguished, and the remaining char started to glow. It is visually identified by the shift from a bright yellow flame to a glowing, less luminous char. The end of char combustion is indicated when the particle's mass showed a plateau in the degradation profile, signifying that all the char had been consumed.

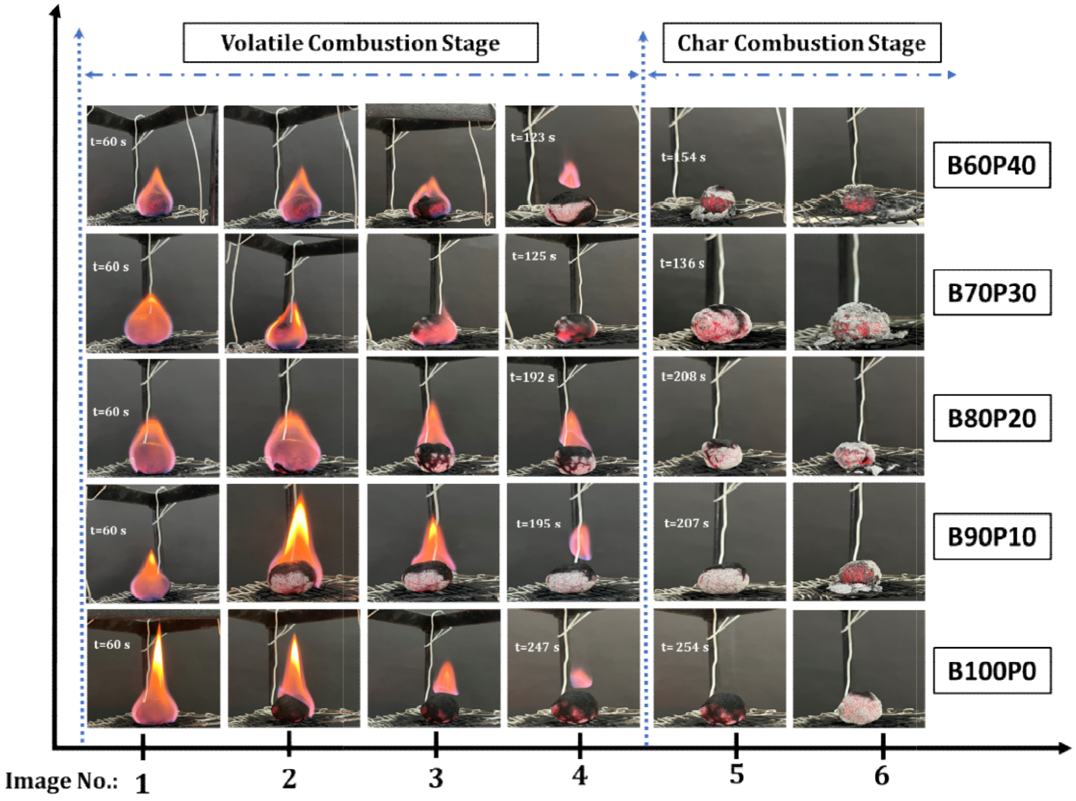


Fig. 4.1 Flame behaviour of various blended fuel samples of 20 mm diameter

The times indicated in the figure mark the start and end of the volatile flames and the beginning of char combustion. The initial indication of ignition is marked by a flash flame appearing on the surface of the fuel sample, which then develops into a bright yellow flame. This suggests that the combustion of volatile matter is likely ignited first in the gaseous phase. The volatile flame gradually expands, smoothly surrounding the fuel particle due to reactions in the gas phase. This indicates a homogeneous ignition mode that is directly influenced by the volatile content of the sample. The biomass sample contains high volatile matter, as shown in Table 2.1. The starting and ending points of the '*volatile combustion*' and '*char combustion*' stages are determined through visual observations and the corresponding mass loss behavior of the fuel samples. Since we did not have instruments to measure temperature changes or conduct gas analysis, we relied on precise observable markers to define each combustion stage. Our approach focused on consistent visual observations and the associated changes in mass. This provides precise and reproducible indicators for each combustion stage.

The duration and brightness of flame are influenced by its structure, intensifying from the centre to the edges. As the volatile materials are consumed, the flame begins to fade, marking the onset of char combustion. This process starts even while a volatile flame is still present, creating a spherical burnout front that moves inward and forms an ash shell. Char combustion involves slow gas-to-solid reactions with the char, characterized by higher radiation intensity than volatile combustion. This phase emits significantly more radiation compared to volatile combustion. Interestingly, the bottom part of the fuel particle initiates char combustion before the top part has completely devolatilized. This delay may be due to uneven burning, as the leading edge of the particle receives more heat transfer than the trailing edge [156]. As combustion progresses, the particle size continuously decreases due to thermal decomposition, resulting in changes in shape until the char is entirely consumed [157].

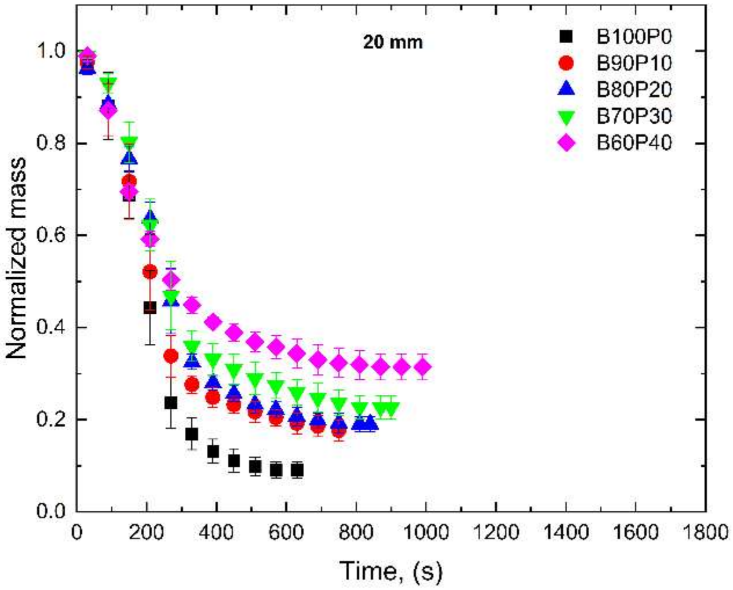
The current study investigates the blending of petcoke with biomass fuel samples in proportions of 10 % to 40 % with fuel diameter of 20 mm. The analysis showed that varying proportions of volatiles and fixed carbon, along with ash content, resulted in different combustion times, even among samples of the same size. Therefore, variations in fuel diameter have not been presented, as the pattern observed with 20 mm diameter considered the variations of the fuel properties. This blending ratio is significant for co-firing applications. Fig. 4.1 also presents the combustion stage of volatile matter for biomass and petcoke samples with a diameter of 20 mm at different blend ratios. During this process, the fuel particle is enveloped by a volatile flame that reaches its peak brightness. Combustion begins when the fuel particles are exposed to the flame, leading to the earlier combustion phases. However, the characteristics of the flame vary depending on the blend ratio of the fuel particles. By analysing images of all the fuel particles, it is observed that the size and brightness of the flame decreased as percentage of petcoke in the blend increased. The experimental results showed that when 40 % petcoke is blended with B. *tulda*, the flame appeared lean, with low luminosity and transparency. Additionally, the luminosity and length of the volatile flame diminished as the percentage of petcoke in the blended fuel particles increased. This reduction is attributed to the lower volatile matter content and the reactivity of the blended fuel particles. Table 2.1 presents the volatile matter content of blended fuel particles at varying percentages of petcoke, which decreased from 72.42 % to 44.69 %. After the volatile matter burned off, the remaining char emitted intense and bright radiation for all blended fuel samples. This emission is noticeable while the volatile substances are still ignited. The radiation continued, and a slight reduction in the size of the fuel sample could be observed until the complete burnout of the char particles. As the combustion of the particles neared its end, the ash continued to glow brightly above the support for a brief period of a few seconds before gradually cooling down. The study concludes that the luminosity and flame behavior observed during the different stages of combustion are influenced by the volatile matter and fixed carbon content in the fuel samples used. Similar findings are reported by Jia *et al.* (2021) in the investigation of the effects of biomass properties on the visualization of combustion phases [157].

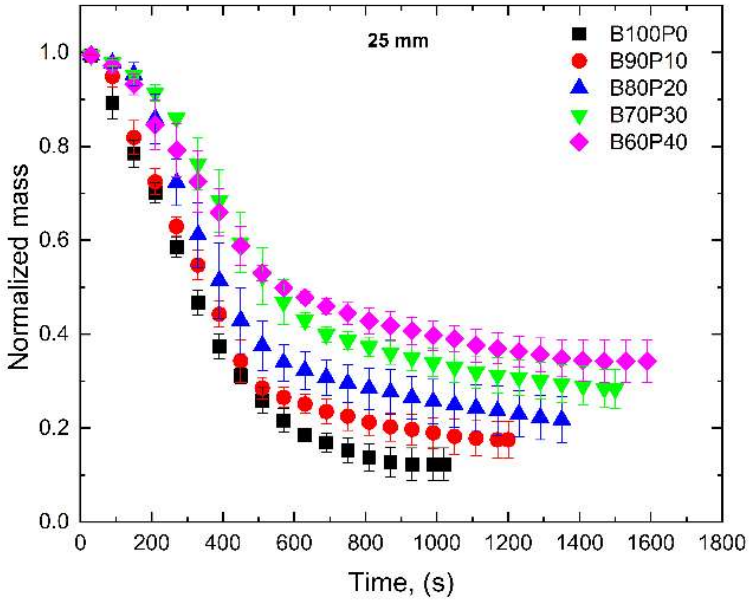
4.1.2 Mass degradation of fuel samples

Fig. 4.2 illustrates the gradual mass degradation of blends of B. *tulda* and petcoke samples during the combustion process, which can be divided into two distinct stages. The first stage involves the ignition and homogeneous combustion of volatile matter, forming an enveloping flame. In the second stage, the combustion of char and volatiles occurs heterogeneously. During the initial minute of combustion, the fuel samples undergo a slight decrease in mass due to heating and moisture removal. This is followed by a self-sustaining volatile combustion stage, characterized by the rapid release and combustion of volatile fractions. The first phase is the devolatilization stage, where volatile materials are released. The second phase, the combustion stage, involves the burning of the remaining porous solid material. Mass degradation is monitored until complete char conversion, leading to a plateau in the mass degradation profile. In each fuel sample, the combustion of volatiles accounts for 70–80 % of the total mass loss, with the raw B. *tulda* (B100P0) showing a significantly higher mass loss.

Blending petcoke in proportions ranging from 10 % to 40 % resulted in significant mass loss. However, incorporating more than 40 % petcoke into the blend does not enhance combustion performance. In fact, at higher concentrations, the mass loss is reduced to less than 50 % and produces unconverted fuel samples. The low volatility and reactivity of petcoke decrease the volatile content in the blended samples, leading to poor combustion behavior and reduced ignition stability. The low reactivity of petcoke is due to its aromatic nature and high ratio of heavy aromatic to aliphatic carbon [77, 138]. Moreover, blending petcoke reduces the porosity of the fuel samples due to its underdeveloped pore structure. This reduction in porosity impacts the volatile combustion stage by restricting the release of volatile compounds, ultimately decreasing mass conversion. The char combustion stage begins after the fuel samples have lost the volatile components. During this phase, mass loss and the char conversion rate slow down as the process approaches complete burnout. Initially, the char combustion phase experiences a high oxidation rate on the char surface, which is enhanced by improved oxygen transport. However, an ash shell forms as char combustion progresses, resulting in a decline in mass loss and char conversion rates.

A temperature gradient and the diffusion of oxygen from the ash shell to the core of the material influence the decrease in mass during combustion. This means that even when the surface of the char cools down, the core continues to burn, resulting in a slower rate of mass loss. The blended fuel sample B60P40 exhibits a higher char conversion rate than the other samples due to its low ash content and higher fixed carbon content. Single-particle combustion experiments used particle sizes of 20 mm, 25 mm, and 30 mm. The mass loss during the volatile and char combustion stages varied for each fuel sample. However, the particle size did not appear to influence the variation in the mass loss profile among the different samples during these stages. On the other hand, particle size did have a significant impact on combustion time. The following sections present a comprehensive analysis of the combustion process, including the effects of particle size, surface area to volume ratio, and the blend ratios of B. *tulda* and petcoke.





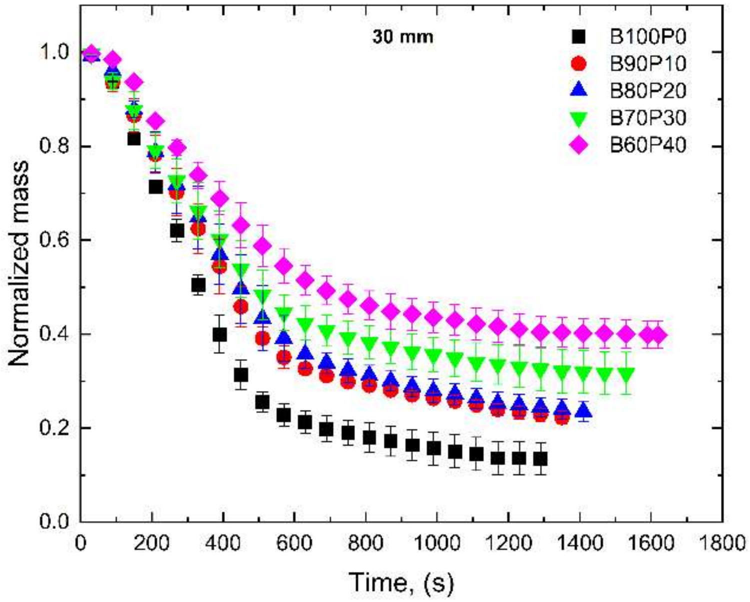
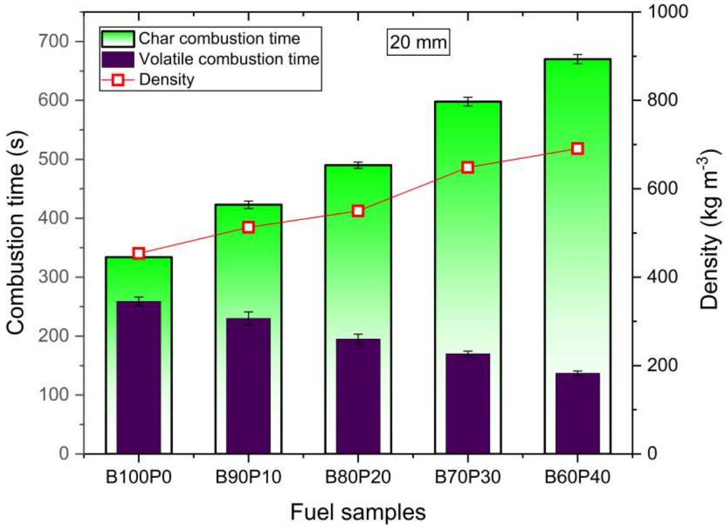
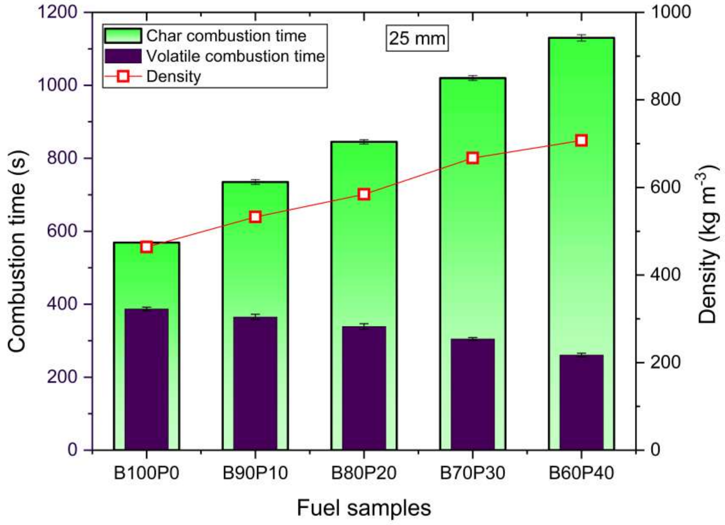


Fig. 4.2 Mass degradation profiles of fuel samples with different diameters

4.1.3 Volatile and char combustion

The volatile combustion stage begins when a visible flame appears on the fuel particle, signifying the ignition of volatile gases. This stage ends as the flame diminishes and fades with the consumption of volatile matter. It is characterized by bright, luminous flames. The char combustion stage starts once the flame is extinguished, leaving the remaining char to glow. This stage marks the transition from a bright yellow flame to glowing char and concludes when the particle's mass stabilizes; indicating the complete consumption of char. However, there is a delay between attempting to ignite fuel samples using an external heat source and the actual ignition. This delay occurs because the moisture in the sample needs to evaporate first, and the sample must reach a specific temperature. A visible flame emerges once this ignition delay has passed, marking the beginning of the volatile combustion stage. During this stage, heating the sample releases volatile components that facilitate gas-phase ignition, leading to intense combustion and a bright, luminous flame. The time required for complete devolatilization of the fuel samples varies depending on the blend ratio of B. *tulda* and petcoke. Fig. 4.3 illustrates the time required for each combustion stage across various fuel samples. As the percentage of petcoke in the blend increases, there is a noticeable decrease in the duration of volatile combustion. This trend is consistent among blends such as B80P20, B70P30, and B60P40. The combustion time of petcoke is influenced by two main factors: its poorly developed pore structure and its combustion characteristics. Petcoke is dense and lacks visible pores or cracks on its surface, making it challenging to release volatile fractions [73]. The combustion time for char increases as the mass fraction of petcoke in the fuel samples increased from 10 % to 40 %. This increase is due to the higher fixed carbon content in petcoke, which results in a longer char combustion time. The extended combustion duration is primarily due to the stronger carbon-carbon (C-C) bonding within the fixed carbon, which enhances its radiation capacity and energy levels [157]. In contrast, raw B. *tulda* (B100P0) has a shorter char combustion time due of its lower fixed carbon content. These effects are most evident in experiments using 20 mm particle diameters, followed by those with 25 mm and 30 mm diameters. The front edge of the fuel samples experiences higher heat transfer due to its direct exposure to the initial heat source and the lack of thermal resistance from the layers above. Additionally, the greater intensity of the flame and the temperature gradients at the front edge, along with the material properties and temperature distributions at that location, contribute to increased radiative heat transfer. Biomass typically has lower calorific values, which lead to lower peak temperatures at the front edge. In contrast, petroleum coke has a higher calorific value, resulting in higher combustion temperatures, creating steeper thermal gradients and localized areas of intense heat transfer. As a result, the blended fuel samples experience higher heat transfer and flame temperatures at the front edge.





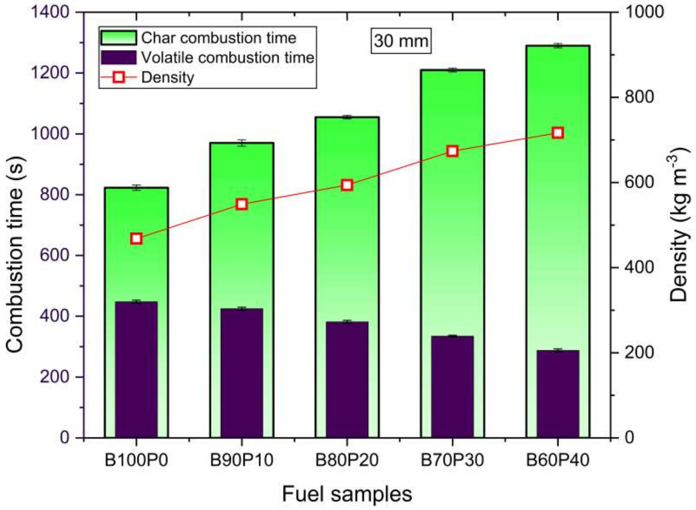


Fig. 4.3 Volatile and char combustion time of fuel samples with different diameters

The density of particles significantly affects the combustion performance of blended fuel particles. Fig. 4.3 illustrates how the particle density of fuel samples changes at different blend ratios. As the proportion of high-density petcoke in the blended fuel increases, the overall particle density also increases. This increase influences mass degradation during the volatile and char combustion stages, energy requirements and thermal conductivity. Higher density results in greater internal and external resistance, hindering the diffusivity of the oxidant and causing longer combustion times for both stages. Li *et al.* (2020) reported similar findings [158]. The unique structures and chemical compositions of B. *tulda* and petcoke account for the differences in combustion durations and flame behaviors of the blended fuel samples. The combustion experiments indicated that the volatile matter content affects the time required for volatile combustion, while the fixed carbon content determines the duration of char combustion. Additionally, the ash residues from these experiments are analyzed to gain a deeper understanding of combustion behaviour from an elemental composition perspective.

4.1.4 Ignition mass flux

Ignition mass flux refers to the rate at which fuel is delivered to the combustion zone per unit area and time during ignition, typically expressed in units such as kg-m^{-2}·s. Fig. 4.4 illustrates the ignition mass flux of various blended fuel samples. Several factors influence this parameter, including the fuel type, the density of the fuel samples, the concentrations of fuel and oxidizer in the mixture, and the operating temperature. Engineers consider ignition mass flux during designing various combustion systems, including industrial burners. This study explores combustion in two stages: volatile and char. The ignition mass flux for each stage is estimated separately. It is found that the ignition mass flux associated with volatile combustion increases as the percentage of petcoke in the blended samples increases. As the percentage of petcoke increases, the amount of volatile matter in the blend decreases, which requires more fuel to be delivered to the reactor over time. Fuel samples with a higher percentage of petcoke ignite more quickly because petcoke contains less volatile matter, leading to an increased ignition mass flux during the volatile combustion stage. At higher percentages of petcoke, the mass of fuel ignited and consumed during this stage is significantly greater. Conversely, when examining the ignition mass flux profile related to char combustion, an increase in the percentage of petcoke leads to a decrease in ignition mass flux. This reduction is due to the high fixed carbon content in petcoke, which requires significant energy to break the carbon-carbon (C-C) bonds. Consequently, this energy requirement delays the breakdown of chemical bonds and macromolecular structures, slowing the conversion process of char toward complete burnout [159].

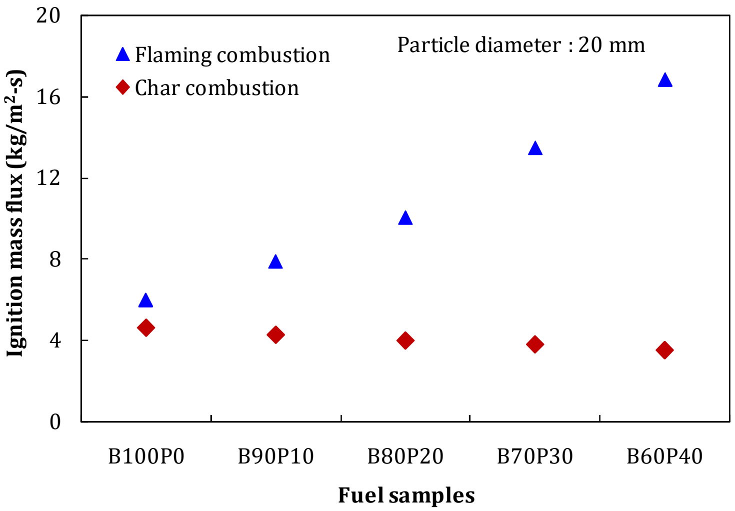


Fig. 4.4 Ignition mass flux of flaming and char combustion of blended fuel samples

It is observed that the ignition mass flux decreases as the percentage of petcoke in the fuel samples increases, particularly when considering complete combustion time. This reduction is mainly attributed to the higher density of the fuel particles as the percentage of petcoke increases. While the fuel density does not directly impact the pyrolysis process of the blended fuel samples, it does affect the conversion time. The decrease in ignition mass flux corresponds with the trends observed during char combustion, highlighting the significant role of char combustion in influencing the overall combustion rate.

Fig 4.2 illustrates the total mass loss across all thermal stages, with fuel samples having higher biomass blends showing greater mass loss due to their increased volatile content. Conversely, Fig 4.4 depicts the ignition mass flux in the flaming zone, where volatiles are crucial. Fuel samples with higher petcoke blends, which contain lower volatile content, ignite at higher temperatures and need more mass per unit area to maintain flaming, leading to a higher ignition mass flux.

4.1.5 Effect of surface area to volume ratio on combustion time

In a single-particle experiment, particles of varying diameters (20 mm, 25 mm, and 30 mm) are analyzed to understand how particle size affects combustion time. Combustion time refers to the duration during which the fuel and oxidizer undergo chemical reactions [160]. This duration can vary based on several factors, including the type of fuel, the size of the fuel samples, and the characteristics of the combustion system. Understanding combustion time is essential for various applications, such as optimizing the combustion process, improving efficiency, and reducing emissions. This study examines the impact of the surface area-to-volume ratio, which is related to the size of the fuel samples, on the combustion time for blends of B. *tulda* and petcoke. Fig. 4.5 shows that the combustion time decreases as the surface area-to-volume ratio increases. This trend shows that smaller particle diameters result in shorter times for complete combustion. Smaller particles exhibit higher reaction intensity due to their larger surface area, which leads to faster combustion rates. This finding is consistent with the research conducted by Das *et al.* (2021) [65]. As the surface area of a fuel sample increases, the coupling between heat and mass transfer improves, which is crucial for effective particle conversion. Heat and mass transfer occur more quickly with a greater surface area, resulting in higher conversion rates. This is because particles with larger surface areas heat up more rapidly through external convection and radiation, thereby accelerating the conversion process, as reported by Momeni *et al.* (2013) [69].

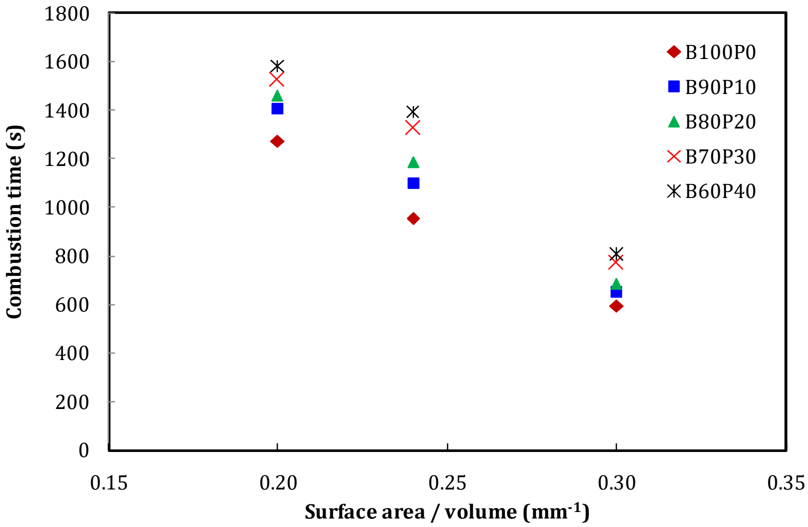
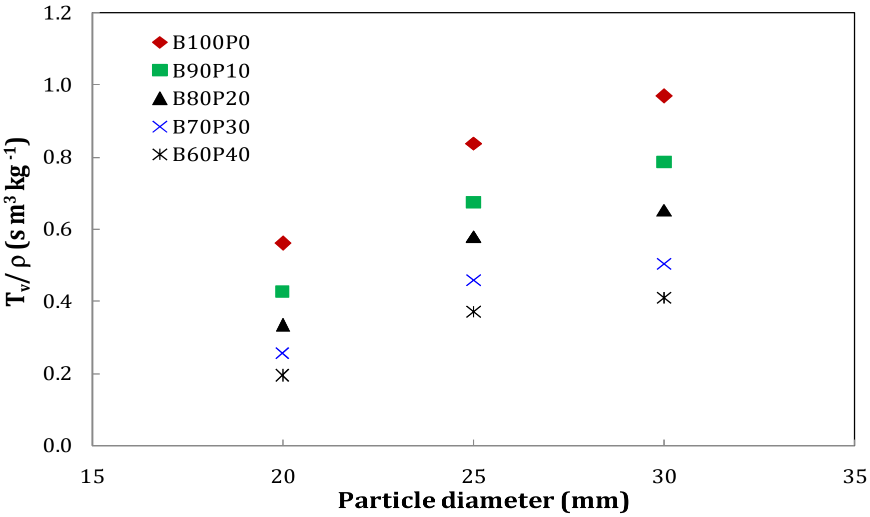
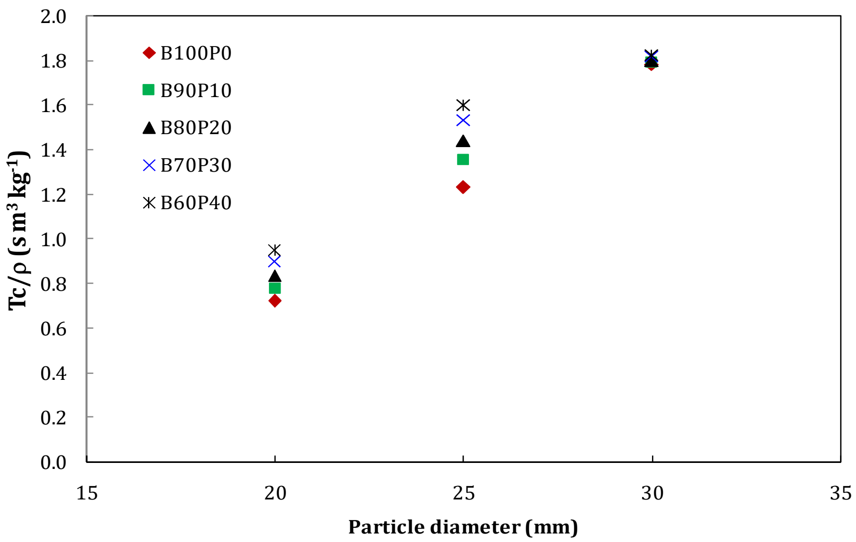


Fig. 4.5 Combustion time with respect to surface area/volume ratio of blended fuel samples

Fig. 4.6 presents the combined effects of volatile combustion times (denoted as T_v) and char combustion times (denoted as T_c) on fuel samples with varying ratios of B. *tulda* and petcoke blends. The density of all fuel samples has been normalized based on the combustion times of volatiles and chars to understand better how particle size and density influence the fuel consumption rate during the different combustion stages. The normalized flaming times vary across different fuel particle sizes. However, the normalized char combustion time remains nearly the same for all fuel particle sizes. During the char combustion phase, the conversion rate is influenced by parameters such as surface area, surface accessibility, and alkali and alkaline earth metals in the biomass sample. These factors create a synergistic effect that enhances the reactivity of the fuel samples. Despite the differences in surface morphology and reactivity between the B. *tulda* and petcoke blends, the time required for complete char conversion in the blended samples shows only slight variation throughout the combustion process. In this context, particle size and the surface area-to-volume ratio are the primary factors influencing this conversion. An increase in particle diameter leads to longer combustion times for both the volatile components and the char, suggesting that the solid-phase reaction of char is slower than the gas-phase reactions during the volatile combustion stage. Several factors contribute to the decrease in the porosity of char particles. These factors include higher fixed carbon content, increased diffusion resistance, and the formation of ash shells around the fuel samples after devolatilization. As a result, access to the oxidizing medium is limited, which slows down the char combustion. It is crucial to maximize the effective surface area for reactions by enhancing the diffusion of the oxidizing medium to improve the combustion performance.



(a)



(b)

Fig.4.6 Density normalized for blended fuel samples (a) volatile combustion and (b) char combustion

4.1.6 Validation using literature results

Several researchers have conducted single-particle combustion experiments using various fuel samples under different experimental conditions. This study compares combustion performance with findings from other referenced research [63, 65, 69, 71, 158, 159, 161-164]. Table 4.1 presents the physicochemical properties of the fuel samples utilized in these experiments. These studies aimed to evaluate how particle size affects the duration of combustion stages. The diameter of the particles has a significant effect on the surface area-to-volume ratio, as well as on heat and mass transfer across particle boundaries during combustion. All these studies categorized combustion time into two primary stages: flaming time, which is associated with the combustion of volatiles, and glowing time, which pertains to the combustion of charcoal. The differences in combustion times observed across the studies are mainly attributed to variations in the physicochemical properties of the fuels used.

Riaza *et al.* (2017) investigated the combustion behavior of woody biomass and bituminous coal with varying particle sizes [63]. The biomass particle sizes ranged from 3 mm to 610 mm, while the coal particle sizes ranged from 1 mm to 300 mm. The study observed that both fuel types exhibited different ignition and devolatilization characteristics. Specifically, the time taken for volatile combustion accounted for 40 - 50 % of the total combustion time for biomass, whereas for coal, it is only 10 - 20 %. The study concluded that biomass particles can be larger than coal particles to achieve the same burnout time, primarily due to their higher volatile content and greater reactivity. Das *et al.* (2021) conducted a study to investigate that blending of wood with coal at different percentages, particle diameters, and densities affects combustion performance [65]. The study indicates that the surface area-to-volume ratio decreased as the particle diameter increased. This reduction meant less surface area is available for efficient combustion, leading to a decreased flaming rate, which is crucial for determining the devolatilization rate. However, the study reported an insignificant variation in the volatile combustion stage related to particle diameter. Momeni *et al.* (2013) investigated how particle shape (spherical versus cylindrical) and operating conditions influence combustion characteristics [69]. The findings revealed that spherical particles have faster conversion rates than cylindrical particles. This increased rate is attributed to higher surface area-to-volume ratio of spherical particles. The study concluded that using spherical biomass particles with similar diameters and a higher surface area-to-volume ratio leads to quicker and more complete combustion in co-firing plants. Tripathi *et al.* (2022) also examined the effects of particle diameter on Refuse-Derived Fuel (RDF) combustion [71]. The study indicated that as the particle diameter increases, the devolatilization rate decreases. This slower rate is attributed to a reduced heat flux to the particle as its diameter increases, leading in a slower burning rate per unit mass of the particle. Li *et al.* (2020) studied the combustion of single coal particles, examining three different types of coal, lignite, bituminous, and anthracite, under O_2/H_2O conditions [158]. The study found that the temperature on the fuel particle surface increased rapidly, reaching its peak in less than 80 seconds, and then decreased until burnout during the initial char combustion stage. It is observed that the oxidation rate of char surface is more intense than the centre of the char due to better oxygen availability. The burnout time for anthracite is longer than that for lignite, which can be attributed to anthracite's higher fixed carbon content and lower reactivity. Additionally, higher oxygen concentrations resulted in higher particle temperatures, leading to shorter burnout times. Qi *et al.* (2021) found that biomass particles ignite earlier and have greater combustibility than coal particles, primarily due to their higher volatile content [159]. The study demonstrated that the gas-phase combustion of volatiles occurs before the heterogeneous oxidation of char in the case of biomass particles. As the volatile content increases, the ignition delay time decreases. The average burnout time for volatiles in biomass particles is 40 – 45 milliseconds, whereas coal particles have longer burnout times in an N_2/O_2 environment. Furthermore, biomass and anthracite particles exhibit shorter burnout times than lignite and bituminous coal particles due to their lower absolute volatile content.

Riaza *et al.* (2014), (2017) investigated the combustion behaviors of various materials, including olive residue, sugarcane bagasse, pine sawdust, and torrefied pine sawdust, in both air and O_2/CO_2 atmospheres [161, 162]. The study found that sugarcane bagasse has a longer average burnout time due to its higher volatile content. Moreover, it is observed that the combustion of homogeneous volatiles and the heterogeneous combustion of residual char exhibit similar behavior, with burnout times decreasing as the oxygen mole fraction increases. In another study, Gnanendra *et al.* (2012) compared the flaming and glowing times of wood and briquette fuel particles in spherical form [163]. The study found that the flaming times for both fuel types are similar. However, briquettes displayed a longer glowing time, which is attributed to the higher density of the briquette spheres. Yang *et al.* (2018) observed that as particle size increases, the ignition of volatile gases also increases. For instance, a particle with a diameter of 0.5 mm has a combustion time of 3 to 4 seconds [164]. In contrast, a particle with a diameter of 2 mm burns for 10 to 14 seconds, and for a 6 mm diameter particle, the combustion time extends to 40 to 80 seconds.

Table 4.1 Physicochemical properties of fuel samples used in literature and present study

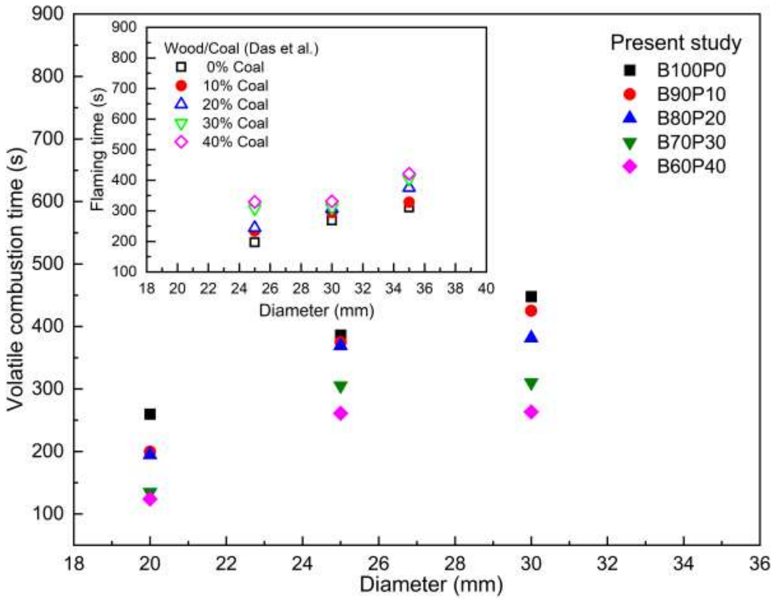
Fuel samples	Physicochemical properties				Calorific value (MJkg^{-1})	Size / diameter (mm)	Reference
	Moisture (%)	Volatile matter (%)	Ash (%)	Fixed carbon (%)			
White wood pellets	7.81	91.84 (daf)	0.99 (dry)	8.16 (daf)	17.75	3 mm–610 μm	[63]
Coal	5.5	40.1 (daf)	1.2 (dry)	59.5 (daf)	32.7	1mm-300 μm	
Wood	10.34	75.76	1.59	12.31	17.1	25, 30, 35	[65]
Coal	2.51	34.57	15.74	47.18	19.56	25, 30, 35	
Pine wood	9.3	77.4	0.3	13	16.98	3	[69]
RFD	5.3	77	18	5	20.3	17.6 - 25.7	[71]
Lignite	16.17	26.29	5.09	52.45	-	6 mm (spherical shape)	[158]
Bituminous	5.21	30.2	8.02	56.57	-		
Anthracite	1.01	8.56	11.81	78.62	-		
Corn straw	-	73.34	7.08	19.58	18.0	125–150 μm	[159]
Wheat straw		60.91	23.32	15.77	13.8		
Ximeng lignite		38.41	17.15	44.44	18.9		
Olive residue	-	71.9	7.6	20.5	19.9	75 -150 μm	[161]
Bagasse	-	87.8	4.2	8.0	16.3		
Pine sawdust	-	79.8	3.8	16.4	18.9		
Torrefied pine	-	75.5	4.2	20.3	20.2		
Steam exploded pellet (SP)	7.2	79.4	4.2	20.6	20	3 mm - 610 μm	[162]
Bio digested waste briquettes	10	70	11	9	14.5	Diameter: 65, height: 55	[163]
Willow chips	6	74	6	14	17.05	0.5 × 1.5 mm	[164]
B.*tulda*	8.32	72.42	2.41	16.85	17.85	20, 25, 30	Present study
Petcoke	1.73	9.87	0.98	87.42	38.22	20, 25, 30	

The present study observed consistent results regarding the combustion characteristics of blended fuel samples. Table 4.2 compared the combustion characteristics from various studies. The size, shape, density, and volatile content are critical parameters that significantly affect the combustion behavior of the fuel samples. Fig. 4.7 compares findings from three studies on flaming and char combustion time for different fuel sample diameters. The results indicate that flaming and char combustion times display similar trends across all studies. It is important to highlight that the time required for char combustion is longer than the devolatilization time of fuel samples. This trend increases with a larger sample diameters, corresponding to a decrease in the surface area-to-volume ratio. The extended char combustion time observed in wood/coal blends and B. *tulda*/petcoke blends can be attributed to their high fixed carbon content and low porosity. In the case of Refuse-Derived Fuel (RDF), its high ash content contributes to the longer char combustion time. Thus, it is clear that factors like particle size, surface area-to-volume ratio, and the physicochemical properties of fuels significantly affect conversion efficiency in co-combustion systems. However, the results of these studies can vary due to differences in the fuel samples and experimental conditions.

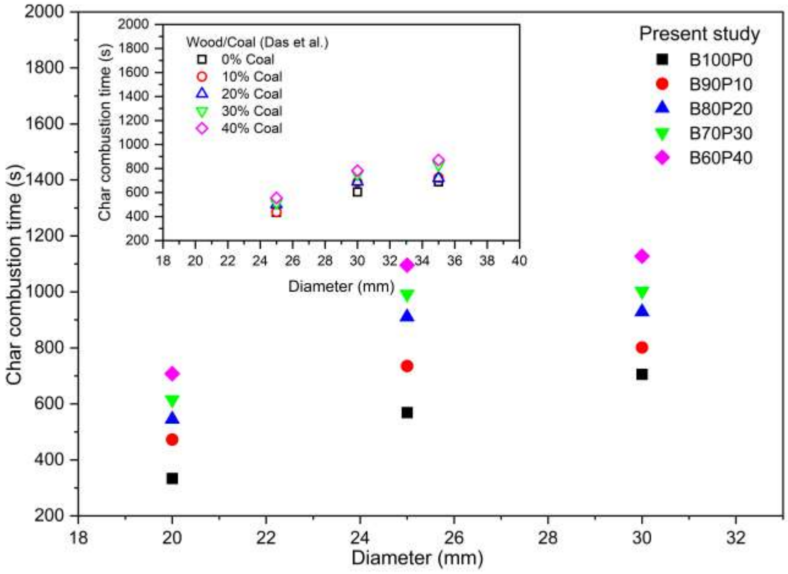
Table 4.2 Comparison of combustion characteristics

References	Comparison of combustion characteristics
Riaza *et al.* (2017) [63]	*Flame behavior*: Biomass particles ignite with a volatile flame that lasts 40 to 50% of the total combustion time, while for coal; the flame duration is only 10 to 20%of the total combustion time. *Combustion characteristics*: There are two stages of combustion: volatile combustion and char combustion. Due to its higher volatile content and reactivity, biomass can produce a larger flame than coal, for the same burnout time. Under the tested conditions, coal particles (sized 300–355 μm) exhibited burnout times similar to those of biomass particles sized 600–1000 μm. *Effect of particle* size: Burnout times are analysed for different particle sizes. Coal: ○ 600–710 μm: 4.1 seconds ± 1 second ○ 710–1000 μm: 6.6 seconds ± 0.9 seconds Biomass: ○ 600–710 μm: 1.5 seconds ± 0.4 seconds ○ 710–1000 μm: 1.7 seconds ± 0.5 seconds
Das *et al.* (2021) [65]	*Flame behavior*: Volatiles burn in a spherical flame during the flaming combustion phase, followed by a more extended char combustion stage characterized by a glowing flame. *Combustion characteristics*: Flaming combustion results in a rapid mass reduction of 80-90%, primarily due 70-80% volatile content in biomass. In contrast, char combustion slows down over time because ash accumulates, which reduces oxygen availability and pressure gradients. Lower coal percentages enhance flaming combustion, while higher coal content increases ash production and extends the duration of char combustion. *Effect of particle size*: The diameter of particles affects the conversion time, with a diameter index ranging from 1.13 to 0.47 for flaming combustion and from 0.63 to 1.23 for char combustion in coal/wood mixtures. The study concludes that particle size, surface area-to-volume ratio, and density are critical for efficient fuel conversion in co-combustion systems.
Tripathi *et al.* (2022) [71]	*Combustion characteristics:* The RDF pellet experienced a 70% loss of its initial weight during the flaming stage, which accounted for 20-25% of the total burn time. In the glowing combustion phase, it lost 10% of its weight and contributed to 75-80% of the burn time, with approximately 20% of ash recovered. The weight loss during flaming was primarily due to a 70-75% loss of volatiles. *Effect of particle size:* For commercial RDF, as the particle diameter increased from 17.6 mm to 25.7 mm, the flaming time increased from 193 seconds to 376 seconds, the glowing time increased from 681 seconds to 1420 seconds, and the total burning time rose from 874 seconds to 1796 seconds. Larger particles reduced heat flux and a lower surface area-to-volume ratio, which slowed down combustion and devolatilization.
Riaza *et al.* (2014) [61]	*Flame behaviour*: AC coal burned heterogeneously, exhibiting delayed ignition and a change in surface colour. HVN (which consists of 90% anthracite and 10% bituminous coal) showed similar burning characteristics, with some volatile flames present. In contrast, UM and SAB coals ignited homogeneously and produced large, sooty flames, followed by char combustion and contrail formation. *Combustion characteristics*: Anthracitic coals demonstrated the most extended burnout times, with AC taking 294 ms and HVN taking 215 ms. In comparison,

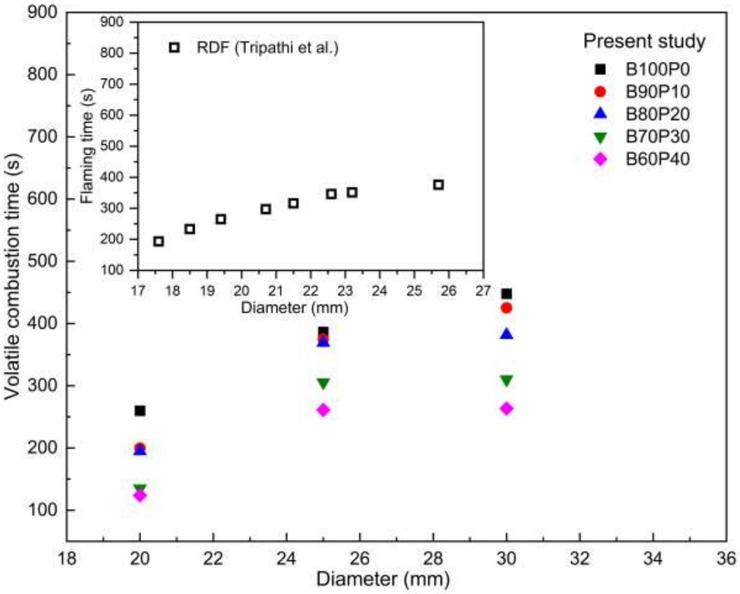
	the bituminous coals burned more quickly, with UM at 114 ms and SAB at 86 ms. *Effect of particle size*: Semi-anthracite particles ignited homogeneously due to their higher volatile content. The ignition behavior of anthracite and semi-anthracite differed from that of lignite, which ignited heterogeneously. This is due to lignite has extensive fragmentation and small fragment sizes (75–150 µm) despite having sufficient volatiles.
Present study	*Flame behavior*: Higher petcoke content in B. *tulda*-petcoke blends leads to reduced flame size, brightness, and reactivity. For instance, when the petcoke content reaches 40%, the flame becomes lean and transparent. Additionally, the volatile matter decreases from 72.42% to 44.69% as the concentration of petcoke increases. *Combustion characteristics*: The initial combustion process shows a slight mass loss due to moisture evaporation, followed by the combustion of volatiles and char. Volatile combustion contributes to 70-80% of the total mass loss. Blending 10% to 40% petcoke results in significant mass loss. However, increasing the petcoke content beyond 40% does not improve combustion performance. *Effect of particle size*: An increased surface area enhances heat and mass transfer coupling, which is crucial for particle conversion. Larger surface areas facilitate quicker heat and mass transfer through external convection and radiation, accelerating the conversion process.



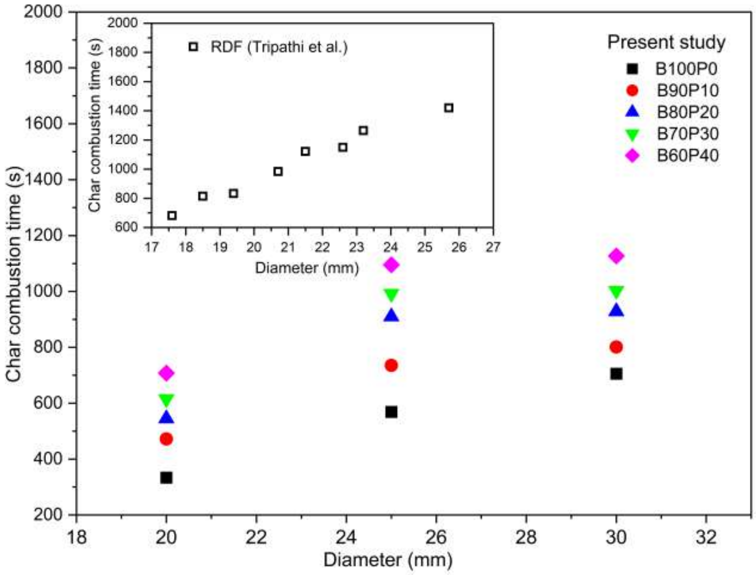
(a)


Present study
B100P0
B90P10
B80P20
B70P30
B60P40
Char combustion time (s)
Diameter (mm)
200
400
600
800
1000
1200
1400
1600
1800
2000
18
20
22
24
26
28
30
32
Wood/Coal (Das et al.)
0% Coal
10% Coal
20% Coal
30% Coal
40% Coal
Char combustion time (s)
Diameter (mm)
18 20 22 24 26 28 30 32 34 36 38 40
200 400 600 800 1000 1200 1400 1600 1800 2000

(b)


Present study
B100P0
B90P10
B80P20
B70P30
B60P40
Volatile combustion time (s)
Diameter (mm)
100
200
300
400
500
600
700
800
900
18
20
22
24
26
28
30
32
34
36
RDF (Tripathi et al.)
Flaming time (s)
Diameter (mm)
17 18 19 20 21 22 23 24 25 26 27
100 200 300 400 500 600 700 800 900

(c)



(d)

Fig. 4.7 Comparison of flaming time and char combustion time for different diameters fuel samples (a) volatile combustion (Reference 65 and present study), (b) char combustion (Reference 65 and present study), (c) volatile combustion (Reference 71 and present study), (b) char combustion (Reference 71 and present study)

4.1.7 Ash characterization

Ash residues are collected after conducting single-particle combustion experiments, as shown in Fig. 4.8. The fuel characteristics of B. *tulda* and petcoke differ significantly, leading to variations in ash compositions. B. *tulda* contains a high concentration of alkali and alkaline earth metals (AAEM), which can contribute to ash agglomeration or corrosion within combustion systems. However, when B. *tulda* is co-fired with petcoke and a synergistic effect occurs that promotes complete char combustion and reduces ash-related problems.

Fig. 4.8 Ash residue of blended fuel particles

This context led to a comparative analysis of how variations in fuel blends and/or co-combustion methods affect ash deposition composition. The characteristics of ash residues are evaluated using analytical techniques such as X-ray Diffraction (XRD) and Energy Dispersive X-ray Spectroscopy (EDX). The XRD spectra of the ash residues from B. *tulda*, petcoke, and their blend are analysed and presented in Fig. 4.9 to investigate the material transport and synergistic interactions between the blended fuel samples. The crystalline components present in the ash of biomass and blended samples are identified by comparing the XRD 2θ values with JCPDS data (ICDD 2003) and previously reported data in the literature. Several high and low-melting minerals are identified in the B100P0 (raw biomass) ash residues, including CaO, SiO_2, KCl, and K_2O. High-intensity crystalline silica forms, such as coesite (SiO_2) and arcanite (K_2SO_4), are typically produced during the carbonization or combustion of biomass. The B100P0 sample is rich in potassium (K), which causes problems like slagging, corrosion, and fouling due to its significant content of arcanite (K_2SO_4), Sylvite (KCl), and Potassium oxide (K_2O). The resultant ash residue primarily consists of potassium (K), which can vaporize and decompose, forming eutectic compounds with low melting temperatures that lead to ash deposition issues [165]. Hence, to address these issues, petcoke is blended with B. *tulda*. This blending helps to overcome the problems, increases the reactivity of the petcoke, and lowers the ash fusion temperature. X-ray diffraction (XRD) findings can be further validated through Energy Dispersive X-ray (EDX) analysis.

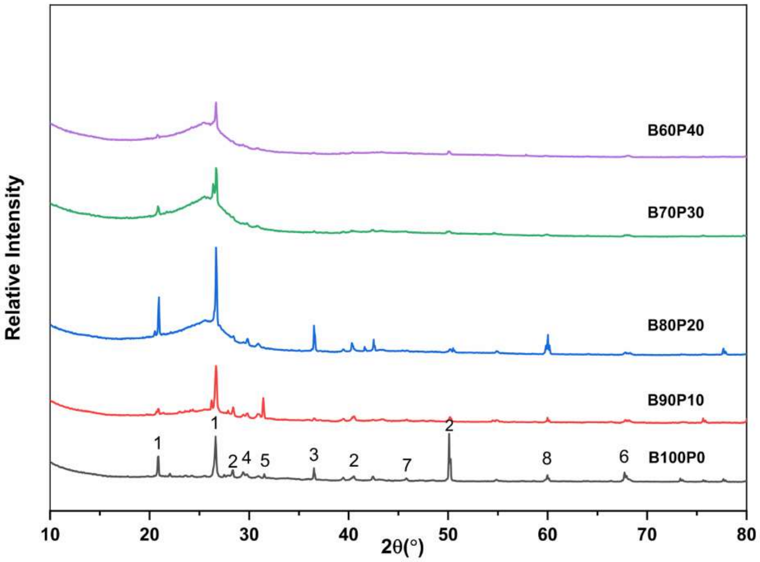


Fig. 4.9 XRD Analysis of ash residue of blended fuel samples

[(1) Coesite (SiO_2) (2) Sylvite (KCl), (3) Potassium Oxide (K_2O), (4) Arcanite (K_2SO_4), (5) Gehlenite ($Ca_2Al_2SiO_7$), (6) Lime (CaO), (7) Dolomite ($CaCO_3.MgCO_3$), (8) Merwinite ($Ca_3Mg[SiO_4]_2$)]

The EDX analysis results of the ash residue from B. *tulda*, petcoke, and their blends are presented in Fig. 4.10. The analysis showed that potassium is the predominant alkali metal in the ash residue of B. *tulda*, constituting approximately 50 wt%. This high potassium content in biomass ash can causes deposition, slagging, and corrosion on the boiler heater surface. These problems can reduce the operational efficiency of the boiler, increase heat loss, and disrupt the intended design of boiler operation [165]. Potassium also acts as a strong fluxing agent and its effect on fuel oxidation is influenced by specific reaction conditions [162]. Potassium can also function as a catalyst during co-combustion, enhancing the char combustion stages. Notably, as the percentage of petcoke in the blend increases, the potassium content in the fuel sample decreases significantly. For example, when blending 20-40 wt% of petcoke with B. *tulda*, the potassium level drops to 25-30 wt%. This observation suggests a potential migration or transformation of inorganic minerals in petcoke, affecting the potassium content in B. *tulda* and promoting enhanced thermal conversion during char combustion.

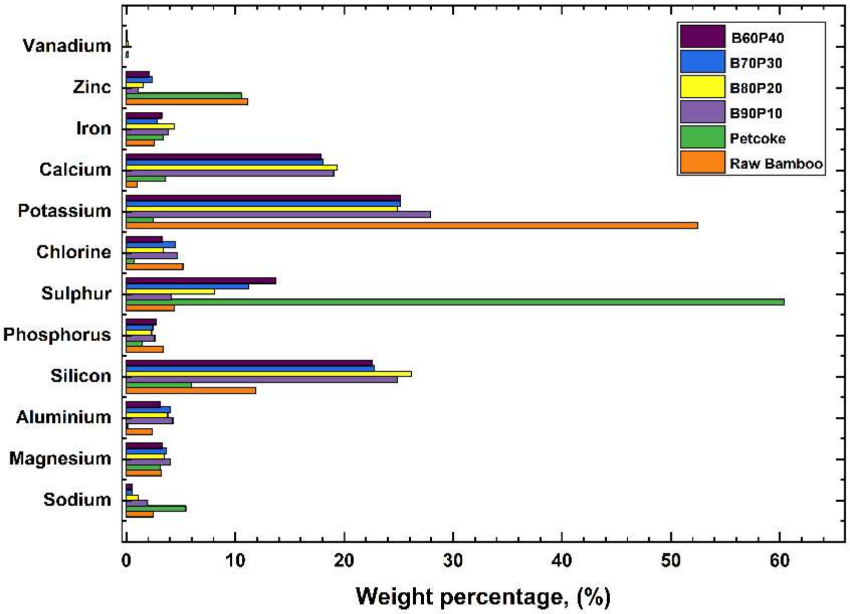


Fig. 4.10 EDX analysis of fuel samples at different blending ratios

The ash residue from petcoke contains approximately 60% sulphur, significantly impacting the migration and transformation of potassium. This sulphur, in turn, can lead to ash-related problems and an increased release of SO_2 [159]. However, a blended fuel sample demonstrated a significant reduction in sulphur content compared to petcoke ash. This suggests that fuel blending have a synergistic effect, resulting in lower potassium and sulphur levels. Blending 40 % petcoke with 60 % B. *tulda* can decrease the sulphur content by 40 wt%. Additionally, increasing the proportion of petcoke in fuel samples has been shown to reduce sodium content significantly. Lowering the levels of elements such as potassium, sulphur, and sodium in the ash residue can diminish the migration of alkali metals. This method promotes a more sustainable and environmentally friendly fuel source and offers a cost-effective solution for co-combustion using B. *tulda* and petcoke.

4.2 Summary

Single-particle experiments are conducted to investigate the combustion characteristics of B. *tulda* and petcoke blends. This study analysed various factors, including flame behavior, mass degradation, particle density, combustion time, and ash residue, to understand their impacts on combustion performance. The study identified two distinct combustion stages for fuel samples with varying blend percentages. Flame characteristics changed with different blend ratios; higher petcoke content reduced luminosity and smaller flame size due to lower volatile matter, leading to lower mass loss. Furthermore, the combustion time is primarily influenced by the percentage of petcoke in the fuel samples. As the petcoke percentage increased, the density of the fuel samples also increased, affecting energy requirements and thermal conductivity, which in turn extended combustion times during both stages. The ignition mass flux of the blended fuel samples is a critical factor in designing combustion systems. A higher percentage of petcoke is associated with increased ignition mass flux during volatile combustion, indicating faster ignition and fuel consumption. Conversely, ignition mass flux during char combustion decreased with higher petcoke content because of its higher fixed carbon content, which affects the overall combustion rate. Smaller fuel particles exhibited shorter combustion times due to increased surface area and reaction intensity, while larger particles burned slowly during char combustion due to diffusion resistance and ash formation. Thus, maximizing surface area is essential for optimizing combustion performance. Comparative analysis of single-particle combustion highlights the significant impact of physicochemical properties, particle size, density, and surface-to-volume ratio on combustion performance.

In a practical application, the co-firing of two fuels can be approached in various ways, depending on the specific combustion system and operational requirements. This method could be particularly beneficial in fixed-bed combustion systems, where maintaining consistent fuel geometry and composition is crucial. Alternatively, fuels can be injected separately into the combustor, which is especially effective in fluidized bed or pulverized fuel combustion systems where fuel mixing occurs dynamically within the combustion systems. Separate injection may offer greater flexibility for controlling combustion conditions and optimizing the combustion process for each fuel based on its unique characteristics. The decision between these methods will depend on the combustion system and practical considerations regarding fuel handling and operational efficiency. In conclusion, blending B. *tulda* with petcoke presents a promising strategy to achieve sustainability and cost-effectiveness in fuel utilization, offering a viable solution for co-combustion with potential environmental benefits.