

Combustion behaviour analysis of coal and biomass ash blends



By

Usman Khalid

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Session 2018-2020

Supervised By

Dr Asif Hussain Khoja

**A Thesis Submitted to U.S. – Pakistan Center for Advanced Studies
in Energy in partial fulfillment of the requirements for the degree of**

MASTERS of SCIENCE

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THERMAL ENERGY ENGINEERING

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THESIS ACCEPTANCE CERTIFICATE

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Abstract

The major problem induced in power plants by biomass is slagging and fouling. Fusion temperature for Biomass is usually very low and is the main reason for slagging, fouling, and agglomeration in the boiler of biomass power plants. This study examined different methodologies comprising ash characterization, ash fusion analysis, slagging, fouling, and agglomeration indices. Coal fly ash (CFA) is mixed with biomass fly ash (BFA) which raises the fusion temperature and reduces the slagging and fouling propensity of ash in biomass-based power plants. The physiochemical characteristics of BFA, CFA, and their blends were evaluated using different characterizations such as ultimate analysis, Thermogravimetric analysis (TGA), Fourier-transform infrared spectroscopy (FTIR), X-ray fluorescence (XRF) used to find the elemental composition, which is critical in finding the slagging, fouling through different fouling and slagging indices. Various indices such as slagging index, fouling index, bed agglomeration index, and ash fusibility index were used to assess the fouling and slagging tendency of all ash samples. The base-to-Acid ratio was also used for this purpose. It was concluded from the characterization of ash samples that by adding coal fly ash, the fusion temperature of biomass increases as the weight percentage of acidic oxides like Al_2O_3 and SiO_2 . The propensity of slagging and fouling is also decreased by the addition of coal and the sample (50CFA+50BFA) amongst all samples shows a low propensity of slagging and fouling.

Keywords:

Ash; Ash fusion temperature; coal-biomass blends; Slagging; Fouling;

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List of Abbreviations

Abbreviation:	Description:
CFA	Coal fly ash
BFA	Biomass fly ash
BBA	Biomass bottom ash
TGA	Thermogravimetric analysis
FTIR	Fourier transform infrared spectroscopy
XRF	X-ray fluorescence
GHG	Greenhouse gases
CHN	Carbon Hydrogen Nitrogen
BAI	Bed agglomeration index
Fu	Fouling index
BTU/lb	British thermal unit per pound (Unit of specific energy)
EJ	Exa-Joule (Unit of energy)
GWh/year	Gigawatt hours per year (Unit of energy output)
tonnes	Unit of mass
° C	Degree Celsius (Unit of temperature)
WHO	World health organization
HPS	High-pressure steam
LPS	Low-pressure steam
AFI	Ash fusibility index
FGT	Flue gas treatment
R _{B/A}	Base to acid ratio
S _d	Sulfur weight percentage
IDT	Initial deformation temperature
HT	Hemispherical temperature
ST	Spherical temperature
FT	Flow temperature
AFT	Ash fusion temperature
DTG	Differential thermogravimetry

Chapter 1 Introduction

1.1 Background

Fossil fuels are the most common source of power generation around the globe. Fossil fuels are diminishing and are a leading contributor to greenhouse gases especially CO₂ [1]. There are other emissions like SO_x and NO_x which are dangerous for living beings on the planet and will eventually diminish the ecosystem [2]. As fossil fuels are depleting, the sustainability of energy is a major challenge for the oil and gas sectors to preserve their reserves. Among fossil fuels, oil and natural gas are believed to be fast diminishing energy sources, while coal is a significant contributor to meeting future energy demands on earth as reserves of coal are expected to last for another two centuries. While oil and natural gas reserves will deplete in the next forty and sixty-five years respectively [3].

As a result, coal continues to be a major source for domestic usage and power generation around the globe [4]. Coal is being used excessively to meet increased energy demands and for industrial development. When using coal, there are two key considerations to keep in mind. The first is the toxic emissions that it generates after combustion, such as SO_x, NO_x, and CO₂ [4, 5]. Secondly, reserves will diminish at a faster rate than they are currently since all energy production will be based on coal. Therefore, having a sustainable and environmentally friendly feedstock for long-term fuel and energy supply is critical[6].

Nonetheless, to reduce emissions, sustainable coal consumption is being developed, as well as global research focused on CO₂ reduction and affordable energy supply. Co-combustion of coal and biomass is a viable short-term solution for decreasing the adverse effects of coal use in power and heat production, but it still confronts unsolved hurdles [7, 8]. In comparison to using only coal, co-combustion of biomass and coal reduces the emission of greenhouse gas (GHG) and hazardous pollutants such as SO_x, NO_x, and CO [9]. Nevertheless, in most commercial co-combustion systems, the maximum ratio of biomass used in the fuel blend is in the range of 5 to 10% (on an energy basis), even though 20% is now achievable, It is technically possible to attain more than 50% [10, 11]. There are other problems like fouling and slagging which can cause by biomass i.e. slagging and fouling in power plants which can reduce the plant's efficiency and increase the generated power's cost [12, 13]. The availability of

significant alkaline earth metals, alkaline, and chlorine components in the ash of biomass causes increased fouling and slagging in biomass-fired power plants, and these elements are the cause of biomass ash fusion temperatures being lower than coal ashes [14, 15]. Major issues such as pollution, reduced thermal efficiency, deposits on heat exchanger tubes, and increased power costs can be caused by slagging and fouling [16-18]. So, mixing coal with biomass can reduce its slagging and fouling tendencies [19].

1.2 Problem Statement

Slagging and fouling are the main problems caused by biomass fly ash (BFA) in a boiler of a power plant because alkaline and alkaline earth metals are present in biomass and cause low ash fusion temperature in biomass [14, 20]. The efficiency of the power plant is reduced due to slagging and fouling caused by biomass fly ash [13, 21]. In power plants slagging and fouling can also lead to major issues such as pollution, reduced thermal efficiency, deposits on heat exchanger tubes, and increased power costs [17, 18]. The well-known operational challenge related to biomass in boilers is agglomeration [22]. Agglomeration in boiler beds is a severe issue that can be hard to identify and spread across the bed, leading to quite an unscheduled stoppage for bed material replacement, negatively impacting the process' cost and dependability [23]. By blending coal with biomass these problems can be reduced [19]. Different slagging and fouling indices such as Base-to-Acid ratio, Slagging index, Fouling Index, Agglomeration Index, and Ash Fusibility Index are appropriate for finding slagging, fouling, and agglomeration propensity in ash samples [24-28].

1.3 Research hypothesis

Coal and biomass could be used together to combat biomass seasonality and provide feedstock for the long term [29]. In addition, blending coal and biomass could be a viable alternative for lowering the unsustainable consumption of fossil fuels and pollution concerns [30]. To remove slagging and fouling problems caused by biomass, coal can be used [20]. As coal contains more quantity of acidic oxides than biomass, so it has a higher fusion temperature [31]. Higher the fusion temperature, lower the slagging and fouling propensities as the ash fusibility index shows that the ashes with higher fusion temperature show lower slagging and fouling tendencies [32]. For this reason, blends of coal fly ash were made with biomass fly ash as by adding CFA, the fusion temperature of biomass fly ash can be increased, and slagging and fouling caused by biomass in boilers can be decreased. To determine the most

effective blending ratio, characterization for each blended sample was done. Additionally, different indices like Base-to-Acid ratio, Slagging index, fouling index and ash fusibility index were used to determine the slagging and fouling propensity to find the blend which is most effective.

1.4 Objectives of study

The study of fouling and slagging behavior of coal-biomass ash blends is the focus of this research. The objective of this study is to evaluate the characterization of coal and biomass blend to determine the chemical and physical properties of coal and biomass individually and how these properties may alter when coal and biomass are blended. This study's experimental work is consistent with the literature. The study's key objectives are as follows:

- To prepare coal-biomass blends and evaluate them with different characterizations at various blending ratios.
- To determine the most appropriate blend with the most synergistic effects.
- To determine the melting behavior of different blends from ash fusion analysis and to investigate slagging and fouling behavior using different indices to find which blend is most optimum.

1.5 Scope of Study

For analyzing slagging and fouling behavior of different blends, fly ash of coal and biomass were produced and described. After collecting the material, the moisture was removed by drying BFA, BBA, and CFA in an oven for 5 hours at 130 °C. All ash samples were sieved to a size of 0.2mm. Different types of coal biomass have different fusion temperatures and unique slagging and fouling behavior depending upon their origin. The scope of this study is shown in Fig. 1.1. In this research, the blending of coal and biomass was done to investigate their propensity for slagging and fouling. The characterization done for these blends were the ultimate analysis, Fourier transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), and X-ray fluorescence (XRF) analysis. Ash fusion temperature was found using an ash fusion analyzer in an oxidation and reducing environment. The experimental data were used in different indices to evaluate their behavior of slagging and fouling of different blends.

Base-to-Acid ratio, Fouling Index, Slagging Index, Agglomeration Index, and Ash fusibility index were the different indices used to calculate their slagging and fouling behavior.

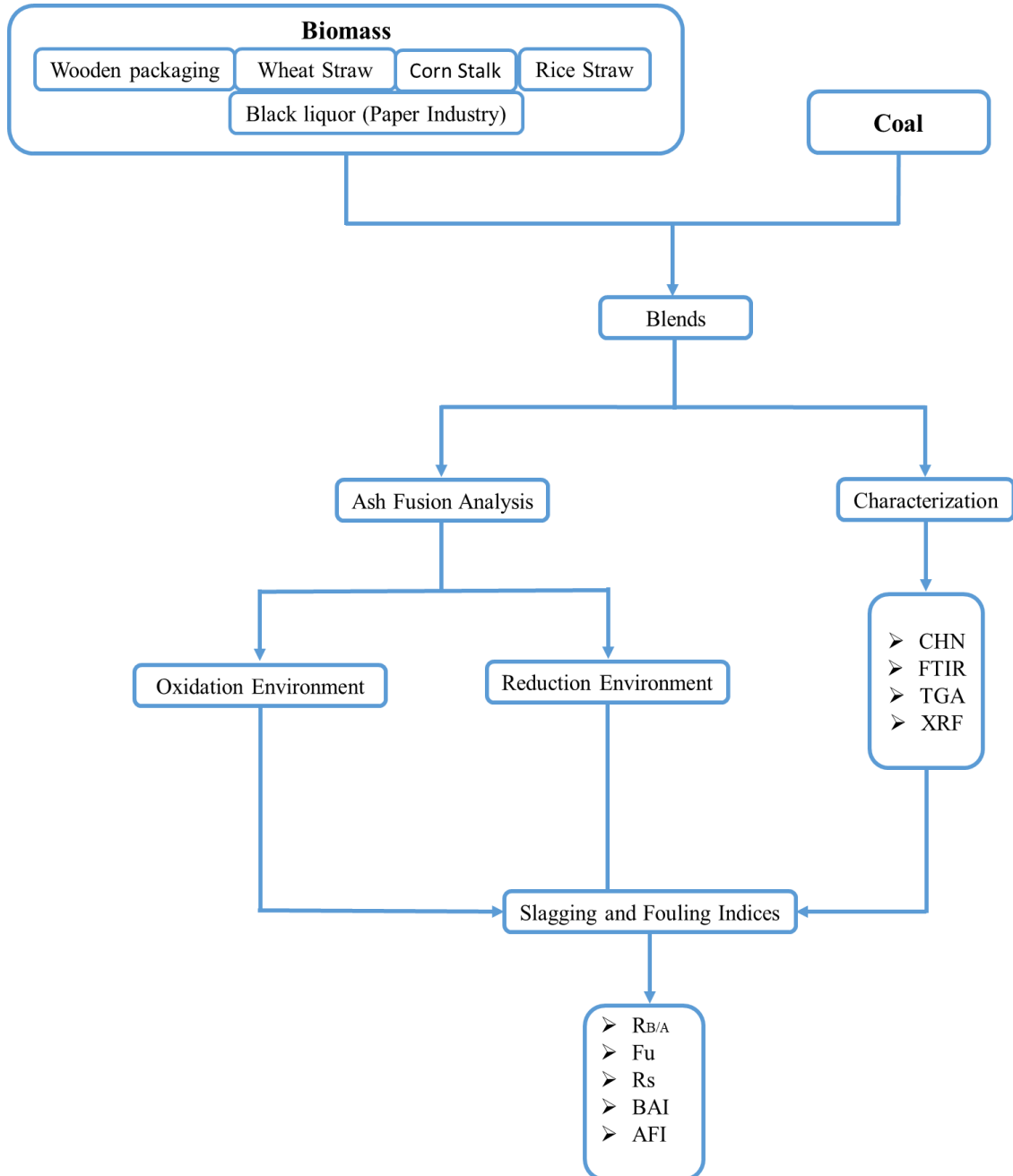


Fig. 1.1 Research Scope of this study

1.6 Flow Chart of Thesis

Fig. 1.2 depicts the thesis flow chart. The goal of this study was to see how biomass and coal ash can be used more effectively and reliably rather than allowing them to generate

harmful emissions or be wasted in landfills. So, a literature review was done for both biomass and coal utilization and current statistics for this purpose. CHN, FTIR, TGA, and XRF were used to prepare and analyze biomass-coal blends. Furthermore, XRF and ash fusion analysis data were utilized in different indices to evaluate their slagging and fouling behavior. In experimentation, ash blends were characterized using CHN, FTIR, TGA, XRF, and fusion temperature investigated in ash fusion analysis to determine their slagging and fouling behavior. The data from the results were fully addressed throughout the result and discussion chapter.

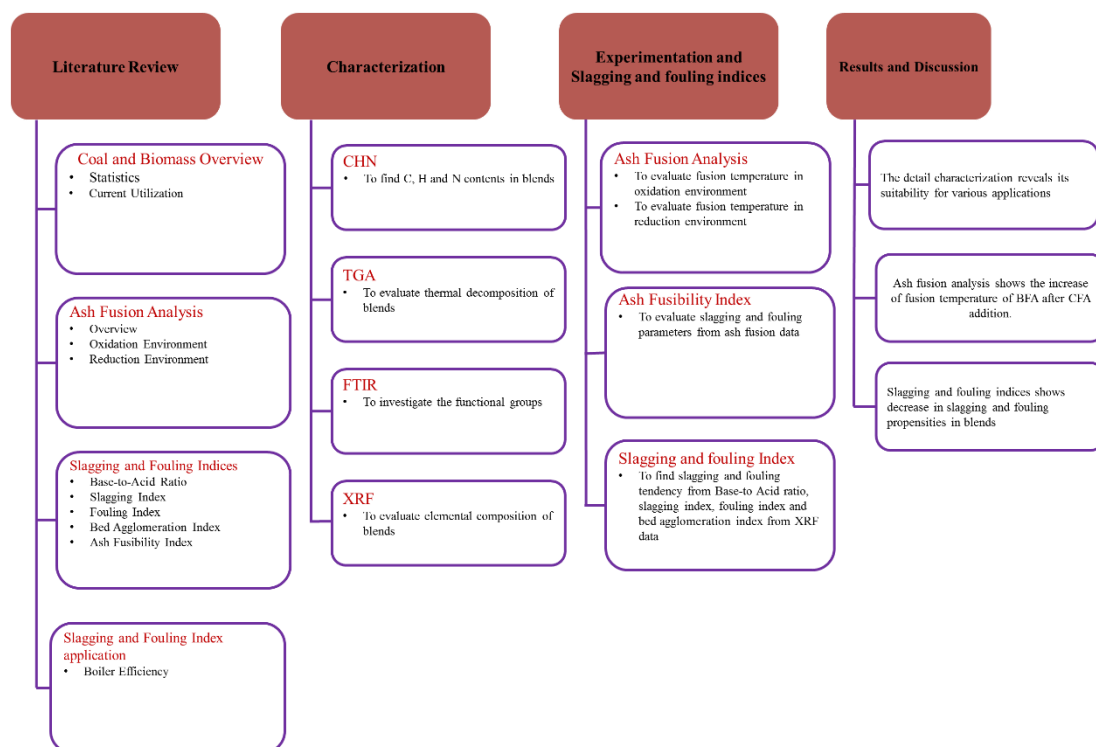


Fig. 1.2 Flow Chart of thesis

Summary

As biomass has low fusion temperature which can cause slagging and fouling in boilers. So, Biomass fly ash will be blended in this study with coal alongside the individual pure samples as the coal used in this study have a high fusion temperature. Biomass fly ash is obtained at top of the furnace which is lighter in weight and is in powder form. In this study, biomass coal and coal fly ash will be blended and used in different characterizations to find their physiochemical properties. Then melting behavior of pure and blended ash samples will be investigated through ash fusion analysis in an oxidation and reduction environment. Then the values of these temperatures would be used to investigate the slagging and fouling

propensities through the ash fusibility index. Then the values of different oxides which will be obtained from XRF will be used to investigate the slagging and fouling propensities. The indices used will be the Base-to-Acid ratio, Slagging index, fouling index, and bed agglomeration index.

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Chapter 2 Literature Review

2.1 Coal Overview

Carbon and hydrocarbons both have high energy density and are produced when coal is burned, making up most of the coal. Throughout the First Industrial Revolution, coal-burning became a practice. From an economic aspect, this source of energy was revolutionary. While polluted air caused by coal is harmful to the environment[1, 2]. Due to rising demand for low-cost electricity, cement, coal, iron, and steel production continues to rise. Based on current extraction rates, coal reserves will last roughly 115 years more than gas and conventional oil reserves, with an anticipated 1.1 trillion tonnes of verified reserves worldwide. The world's coal production is controlled by 10 countries that contribute around 90% of global output. China is the world's biggest coal producer for the last three decades. Over a third of total coal world reserves are present in China. The United States and India contain second and third highest coal reserves in the world[3]. Coal accounts for over 40% of global primary energy use[4]. Coal is the predominant energy source in many underdeveloped countries. All nations agreed in Paris in December 2015 to invest and strengthen intervention to avoid global warming and maintain a low-carbon, sustainable environment. The reduction of greenhouse gases is the purpose of the Paris agreement. [5]. The objectives are difficult to achieve since most developing countries are preoccupied with today and not tomorrow. Toxic waste from power plants is released into the atmosphere, endangering people's health[6]. The large volume of coal dust formed during extractions, as well as transportation, is a source of diseases for employees and residents in the surrounding areas[7].

WHO air quality guidelines are not met in 97 percent of low and medium-income countries in cities with populations greater than 0.1 million[8]. While burning coal is among the contaminants, it's also important to note that point-source residential heating, coal transportation, automotive fuel combustion, and cooking sources all lead to pollution. The ability of an organism to function properly is determined by the air quality it breaths [9]. Figure 2-1 depicts the availability, classification, and path for each sort of coal use effect:

Lignite often referred to as brown coal, is formed from compacted peat and contains (60-75) % carbon and (30-70) % moisture. Lignite is very high volatile and low-rank coal that

is primarily utilized in power plants. It is used in power generation. Ornamental stones are frequently made from polished "jet" lignite[10].

In sub-bituminous coal carbon content on a dry basis is about (71-77) %. It ranges in color from soft black to dark brown, is substantial, and contains a moisture content of (15 -30) %. It contains a heat content from (8300-11500) BTU/lb. It's used to produce energy using steam. For heating water and generating steam fossil fuels like coal, oil and gas are utilized. And this steam is used to run a turbine [11].

On a dry basis, bituminous coal contains carbon contents in a range of (77-87) %. It is a dense black solid with moisture content in the range of 1.5 to 7 percent. It is made up of compressed lignite and can easily break down. It has many applications like the production of coke, used in power plants, and the production of briquettes. It contains more than three times heat content than lignite [12].

Anthracite contains carbon contents in a range of (86-97) %. It has a black vitreous sheen and is highly ignitable coal. It is highly corrosive coal. It is a fuel with no smoke and is generally used in homes and business settings. It has a high burning duration and generates a lot of heat. Sulfur concentration is relatively low in this type of coal [13].

Coal contributes only 0.2% of overall electricity production in Pakistan. It is primarily used to produce heat. It is economical, yet it is environmentally hazardous. Putting the right policies can lead to significant growth.

2.2 Biomass Overview

The resources of biomass have the prospect of being the most abundant renewable resource on the planet. The potential of bioenergy for biomass is roughly 2900 EJ in which the energy that can be sustained is 270 EJ and 4500 EJ is the primary annual output of biomass. Currently, global biomass wastes and residues, including by-products of fiber, food, and forest production, exceed 110 EJ per year; In industrial facilities, concentrated residues are currently used as a source of biomass [14]. Pakistan generates an estimated 220 billion tonnes of municipal solid waste and biomass each year, showing a significant increase in the production of energy. A significant portion of it is wastefully burned in outdoor spaces, causing pollution to the environment. Biomass is utilized as a renewable energy source in energy generation in many prosperous countries, unlike many developing countries where it is

underutilized. A report by the World Bank shows the potential of biomass in Pakistan in different sectors such as rice plants, sugar mills, dairy farms, and municipal solid waste dumps. Leftovers of crops from agricultural fields are unused and they are usually thrown away. Processing crops have the potential of producing energy up to 61,838 GWh/year as crop residue produced is around 25.3 million tonnes per year. Energy potential for harvesting residue is around 448,990 GWh/year as it is produced in around 114 million tonnes per year. Pakistan is expected to collect an organic waste of about 20 million with a rising rate of 2.4 percent. Reliance on traditional fossil fuels can be reduced and ultimately usage of fossil fuels becomes obsolete if biomass fuel technology is adapted [15].

Cellulose, hemicellulose, and lignin are the three main components of biomass. Hemicellulose accounts for 25-30 percent of biomass and it is a polysaccharide composed of shorter chains of around 500 to 3000 sugar units. A significant weight loss occurs above 200 °C as hemicellulose start to degrade at 150 °C. Mostly during the thermal breakdown of hemicellulose, light volatiles is released, resulting in fewer tars and char[16]. Cellulose is a polymer that has a molecular weight of 106 or higher and is the fibrous component of wood and biomass. Because its structure is more crystalline than hemicellulose, cellulose resists heat breakdown. During thermal breakdown, the amorphous portion of cellulose retains hydration water, which is transformed into vapors and leads to a structure burst. Cellulose decomposes at 240-350 °C temperature[17]. Lignin is a component of the plant cell wall that bridges the gap between hemicellulose, cellulose, and pectin. Lignin begins to break down thermally at temperatures of around 280C-500C, producing phenols[18]. The most prevalent way of biomass conversion into energy is direct combustion and around the world, this method is widely employed[19]. Three different ways biomass can be utilized are (i) combustion, conventional and with coal co-firing [20] (ii) for producing heat and generating power from thermochemical treatment [21] while the third process is the production of biodiesel, bioethanol, biogas, and bio-hydrogen [22, 23].

2.3 Biomass power plants

Biomass-fired power plants function similarly to coal-fired power plants, however, due to moisture present in biomass makes it difficult to use in conventional coal power plants [24]. Before being supplied to the combustion unit, biomass must undergo drying pre-treatment for this reason [24]. To eliminate moisture content, biomass firstly is gathered from the source and then processed for the next few days before being stored in a storage tank. Fuel store is used to

store biomass once it has dried naturally, and then it is put into the combustion chamber (boiler or furnace). In the combustion chamber, direct combustion of biomass produces high-pressure steam (HPS). To generate electricity, an HPS turbine is driven by high-pressure steam which is linked to a generator. Then in the combustion chamber, low-pressure steam (LPS) is returned. The exhaust gases and fly ash are removed from the flue gases using the flu gas treatment (FGT) unit.

In most power plants where biomass is used as a fuel source, the organic Rankin cycle is used [25]. Biomass-based power plants typically have lower production capacity than fossil-fueled plants and are smaller in size having a range of 10 to 200 MW [26]. (i) Fluidized bed combustors (ii) grate-based firing systems (iii) suspension burners in biomass-fired power are the most prevalent forms of direct combustion.

For power generation and combining energy in various biomass-fired power plants, the technique used is co-generation. For conserving energy and decreasing environmental risks, Co-generation is the most effective method [27]. In co-fired power generation biomass can also be used in combination with coal [28]. For a short-term solution for the production of energy, the most viable solution is thought to be these co-generation power plants [29]. In recent years to address environmental concerns and also the efficiency and economics of biomass co-generation numerous studies have been conducted [30, 31]. The efficiency of 3 to 30 MW systems varies between 17 and 31% [32]. Different combustion system techniques are employed, each based on different combustor configurations and parameters of design. These are (i) fluidized bed combustion (ii) fixed bed combustion and (iii) pressurized fluid bed combustion.

2.4 Ash Production

Following combustion, ash is an inorganic non-combustible component of the fuel made up of a variety of minerals. Ash around 475 million tonnes are produced a year from burning biomass of seven billion tonnes with a 6.7 percent ash yield [33-35]. Roughly 780 million tonnes of coal are produced annually by coal combustion plants [36, 37]. Once it is exposed to combustion, ash or residue because of contaminants in the feedstock is created in all types of power plant boilers. After combustion, it is a part of the fuel that is non-flammable and composed of mostly silica-based material and minerals [38]. The composition of generated ash varies due to the variable compositions of the various biomass feedstock present [39]. The

energy produced by the feedstock of biomass usually contains high ash contents [40]. Because of the considerable use of coal and biomass in blending with coal, most of the world's ash is produced by India, China, and the United States. The majority of ash is produced in Asia with India leading with 112 million tons per year of ash and China producing a million tonnes of ash. The amount of ash in biomass varies greatly on the type and origin of biomass. The lowest ash content by weight is present in wood chips. Biomass has a low ash fusion temperature and high ash content due to the low base-to-acid ratio and different metal oxides [41]. Due to not applying pre-treatment in biomass and contaminants present when biomass is harvested, there are high ash formation in biomass. Because of these difficulties, biomass combustion systems differ from traditional coal-fired combustion systems.

2.5 Ash Utilization

Biomass ash can be utilized in various applications like cement production, concrete, catalytic applications, ceramic materials, soil treatment, and roadways [42-46]. Due to the presence of poisonous metals or water-soluble harmful chemicals, the use of biomass ash must be carefully analyzed on a case-by-case basis, which necessitates rigorous analysis. This diversity in composition alters the chemical and physical properties [47, 48]. The arrangement of pollutants and the degree of ash sintering influence how biomass ash is used [35]. Ash obtained from cleaner feedstock contains minerals and trace elements and can be used as a soil amendment in forests or as an agglomerating agent in cement, for example. However, the composition of these materials must be quantified and their effects must be thoroughly researched before application [49]. Biomass ash is a resource that can be used for a variety of purposes, including mine filling. It also has the potential to be employed in revolutionary nanotechnology applications in environmental remediation, energy storage applications, and catalysis in material science [50, 51]. The potential for using biomass ash in soil treatments is enormous. The majority (N, O, H, K, sporadically Ca) and minor (P, Cl, S, Mg, Na) and trace elements (Mn, Cu, B, Fe, Zn, Mo) of plant-rising, nutrients, and vital components are present in biomass to refine the regular balance in the system[48, 52, 53].

2.6 Biomass composition and classification

Several variables influence the composition of biomass. For biomass usage in power plants, efficient identification, characterization, and phase composition are critical. Previous research has shown that biomass contains a complex heterogeneous composite like other solid

fossil fuels of biological matter made up of solid phases, fluids, and different minerals. Natural and anthropogenic activities are triggered by various biomass phases via, syngensis, post epigenesis, epigenesis, and pre-syngensis, according to the method, phase development, time, and formation location. Ash content, fixed carbon, alkaline earth metals (Ca, Mg), organic and inorganic components, water-soluble nutrients like P and K, and volatile matter are all abundant in biomass[54]. T, Mn, Mg, K, Na, Si, H, Fe, Ca, O, Al, Cl, C, N, and trace elements are the most prevalent components found in biomass [54]. Moisture, Oxygen, volatile matter, P, Na, Cl, Mn, Ca and K are normally more abundant in natural biomass, whereas H is slightly increased and ash-like Si, Fe, Ti, N, and Al are depleted. The d-spacing of biomass ash is greater, ranging from 0.34 and 0.88 nm. The structure of biomass is semi-crystalline. The intermolecular distance, which varies depending on the complex structure of lignin, opal, hemicellulose, oxalate and cellulose linkages, is around 0.59 to 0.40 nm. The structural elements of biomass include hemicellulose, cellulose and lignin which make up more than 90% of the biomass composition, while other components include proteins and carbohydrates [55]. The use of biomass for producing ash is clear from the study of combustion processes. In biomass-fired power plants, ash is classified into two types: biomass bottom ash (BBA) and biomass fly ash (BFA). Because of feedstock and operational circumstances, BFA and BBA have various qualities and compositions. Typically when biomass is burned, the ratio for ash composition is evaluated by the inorganic elements present in the feedstock of biomass [56]. BFA contains high metal oxides like MgO and Al₂O₃, whereas slag and unburned biomass are high in bottom ash [30]. There are two types of biomass ash: class F and class C. BFA is comprised of oxides like Fe₂O₃, MgO, CaO, Al₂O₃, TiO₂, and SiO₂. This categorization is based on carbonate content. Class C ash is defined as BFA with a CaO content of around 8%. While CaO concentrations are less than 8% and are categorized as class F ash [57]. BBA is often created from the bottom grate while combustion and is constituted of unburned biomass, sand particles, and slag. Its makeup is highly complicated, making it tough to handle and use [57].

2.7 Ash Fusion Analysis

Problems with biomass are strongly tied to its fusion properties as well as its issues related to chlorine and alkali metals. There are slag deposits on heating surfaces of boilers and it is because of ash fusion characteristics [58]. Ash fusion characteristics are a more beneficial technique for providing quantitative data on various characteristics of biomass. To make a

boiler design, Initial deformation temperature (IDT) is obtained from the ash fusion test that depends on various elements present in biomass [59]. The most efficient and direct techniques for evaluating fusion characteristics are ash fusion temperatures such as initial deformation temperatures (IDT), hemispherical temperatures (HT), spherical temperatures (ST), and flow temperature (FT). Ash fusion characteristics depend on both mineral and chemical composition and are a key causing component for melt-induced slagging and agglomeration [60]. IDT increases with increasing Al_2O_3 , Fe_2O_3 , CaO , and MgO contents while decreased with increasing K_2O ash contents. Potassium, Calcium, Aluminum, and silicon are the primary components of slag [61]. It is frequently employed as an assessment index for coal. It is recommended that IDT be used for biomass due to the lack of sensitivity of spherical temperature (ST), hemispherical temperature (HT), and flow temperature (FT) to the components included in biomass. By using 8 biomass and 27 simulated ashes made by combining organic and inorganic oxides at a temperature of 580 and 815 °C, respectively, it was shown that enlarged the biomass species or corresponding ash species and found similar findings [59]. Based on the ash characteristics of the burned 30 biomasses in operational power plants, the authors [62] recently performed research on silicate melt-induced slagging and discovered that IDT may be utilized as the assessment indicator for silicate melt-induced slagging. IDT rises with increasing Al_2O_3 and $\text{SiO}_2/\text{K}_2\text{O}$ but falls with increasing K_2O , SiO_2 , $\text{SiO}_2/\text{Al}_2\text{O}_3$, and $(\text{SiO}_2 + \text{K}_2\text{O})/\text{Al}_2\text{O}_3$. These substances can be sorted in decreasing order of impact on IDT: Al_2O_3 is followed by K_2O , SiO_2 , and then $(\text{SiO}_2 + \text{K}_2\text{O})/\text{Al}_2\text{O}_3$ [63]. Another study, on the other hand, stated that the assessment of biomass Ash Fusion Characteristics (AFC) should be based not only on their elemental composition, with the exception of IDT, but also on the high temperature molten material that provides structural support for the skeleton-like structure in biomass ash [61]. According to Vassilev et al. [64], fluxing minerals like anhydrite, calcium silicate, hematite, etc. decrease AFTs while refractory minerals like quartz, metakaolinite, mullite, and rutile increase them.

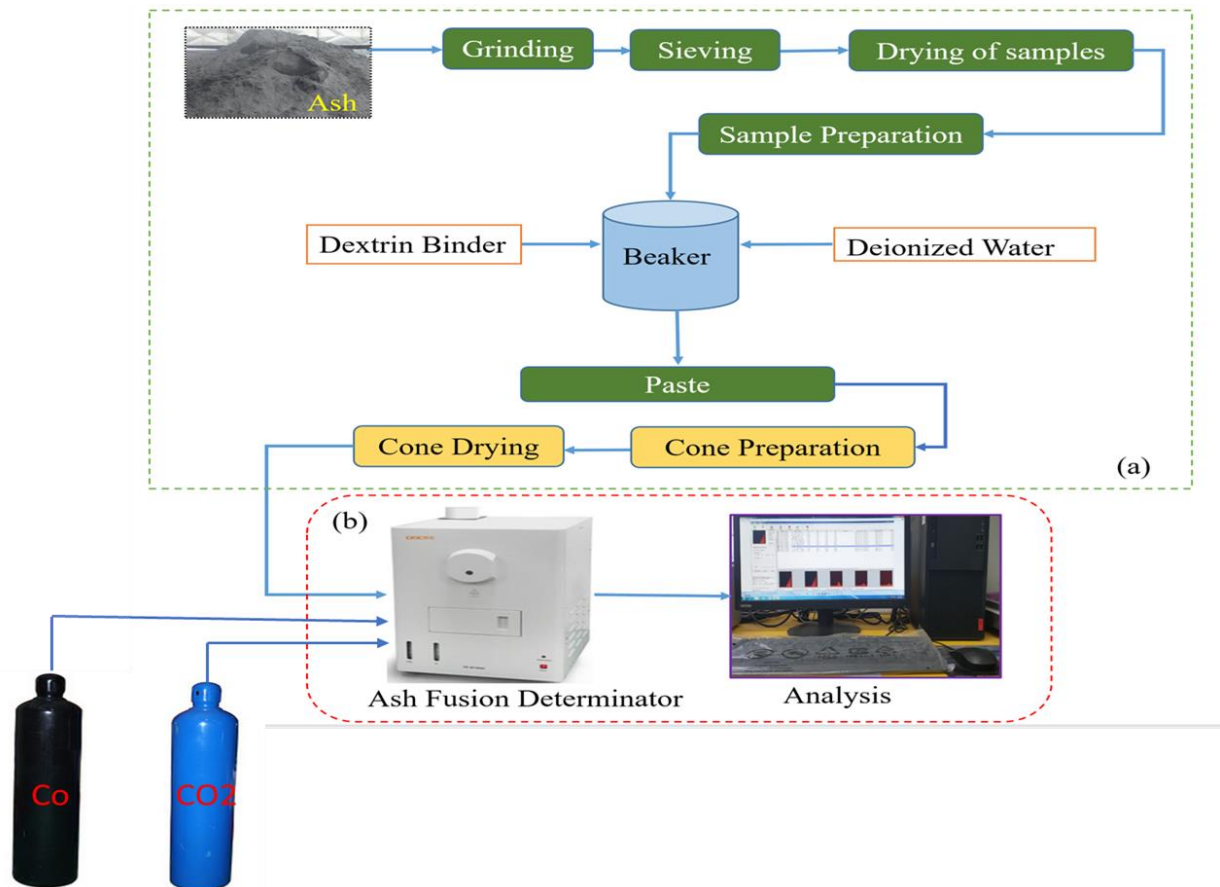


Fig. 2.1 Ash fusion analysis

2.7.1 Slagging and fouling in biomass

There are two types of slagging induced in biomass (i) Alkali-induced Slagging and (ii) Silicate melt-induced slagging. Alkali metals are the main cause of Alkali-induced slagging, particularly sulfates and alkali chlorides. As a result, more consideration ought to be given to the transformation, development, relevant volatile alkali species sequestration, forming methods, and alkali-induced slagging evaluation or criterion indices. The transportation and liberation of alkali metals in combustion gas as a vapor species or solid particles are accomplished during burning, which is associated with the organic structure's degradation (which is mostly constituted of protein, lipid, lignin, hemicelluloses, celluloses, and so on). Alkali metals occur primarily as M-silicates and M-aluminosilicates (M denotes Na and K) [65]. Alkali metals enter the gas phase as both inorganic and organic compounds [66]; As a result, less stable oxides are produced by alkali metals than the other ash-forming elements [67]. At high combustion temperatures, the carbon-hydrogen fuel matrix may also convert the oxides into metal vapor. More volatile and stable hydroxides are produced due to rapid

reactions between water vapors and alkali species. The alkali species then rapidly react with water vapor to create more stable and volatile hydroxides [KOH(g) and NaOH(g)]. During the in-flight phase, some alkali vapor species come into contact with a chemical environment, which affects the eventual transference of the flame [68, 69]. Problems with biomass ash are linked not just to alkali metals and chlorine, but as well as to biomass ash fusion characteristics (AFC). The ability of a fuel to form partially or completely fused slag deposition on the heating surface of a boiler is determined by its AFC [58]. For silicate melt induced slagging, even though lab-scale sintering experiments, thermochemical calculations, and thermal analysis (TGA/DTA) [70, 71] may be employed but a more effective tool for quantifying the characteristics of diverse materials is an ash fusion test. Two additives kaolinite and dolomite can encourage ash fusion behavior of rice straw, wheat straw, and corn straw. As initial deformation temperature (IDT) is increased by kaolinite while dolomite increased flow temperature (FT) [72]. In another study, agglomeration and fusion properties of pure coal, biomass, and their mixtures were evaluated alongside the additive addition of K_2CO_3 in different ratios [73]. In another study, the blending of biomass with coal was done to find the effects on slagging properties and fusion temperature [74]. In another study, slagging characteristics were evaluated in different combustion atmospheres [75]. In another study, a good effect on melting data was observed through fouling and slagging indices [48]. In another study co-firing of biomass with coal was studied [76].

To guide the design of biomass boilers, initial deformation temperature (IDT) is used which is evaluated by biomass ash's component formation [59]. Numerous research has focused on evaluation indices and criterion numbers to approach alkali-induced slagging. These researches provide applicable recommendations for burned biomass, additives, and co-firing fuels in boilers. Jiang et al. [77] calculated slagging in biomass using the same base-to-acid ratio as coal ($R_{b/a} = (Fe_2O_3 + CaO + MgO + K_2O + Na_2O)/(SiO_2 + TiO_2 + Al_2O_3)$). Once the index value is lower than 0.7, the softening temperature (ST) would be lower than 1000 °C; when it is greater than 1.7, the ST is greater than 1200 °C. Even though many evaluation indices have been studied, the majority of them are based on laboratory data with just a handful originating from commercial utility boilers or being validated by industrial practice. In biomass, the use of R_S -based indices [78] can result potentially lead to incoherent results, because biomass contains a low level of Sulphur concentration than coal: $R_s = R_{B/A} \times S^d$ (S_d = Sulphur percentage).

According to Eq. (4), the fouling index F_u to a greater extent could be appropriate for biomass since it provides greater importance to the alkaline components, which are the principal causes of fouling. However, due to their impact on alkali element vaporization, Cl and S contents might be incorporated to improve the result: $F_u = R_{B/A} \times (Na_2O + K_2O)$ [78].

Ash melting behavior of fuels can be comprehensively explained by the ash fusibility index as compared to other typical indices used. The ash fusibility index is calculated by ash fusion temperatures under a reducing and oxidizing environment for coal, biomass, and biofuels (see Table 1). The formula for ash fusibility index is $AFI = (4 \times IDT + HT) / 5$ where IDT represents initial deformation temperature while HT represents hemispherical temperature.

The operating temperature in fluidized bed boilers is very low and they are considered ideal for biomass combustion and are unchanged to fuel properties. On the other hand, induced by inorganic fuel component bed agglomeration is a serious problem in these boilers. If the worst comes to pass, the whole power plant is de-fluidized and shut down without warning [30]. The agglomeration propensity is generally determined by the bed material [79], fuel [80, 81], and operation circumstances. The agglomeration index is used to find agglomeration in biomass boilers. $BAI = Fe_2O_3 / (K_2O + Na_2O)$

Summary

In biomass power plants, slagging and fouling are the major problems. So, there is a need to reduce the propensity of slagging and fouling. The depletion of fossil fuel reserves and damaging emissions must be addressed urgently to conserve some of their reserves and mitigate climate change. Coal reserves will be available for the next 200 years, yet their emissions cause significant harm. But coal has a high fusion temperature and hence a low tendency towards slagging and fouling in boilers. So, it can be used in already build biomass boilers along with biomass to reduce slagging propensity.

As alternative biomass can be used. But the most efficient process which can be used which can be useful to slow down the depletion of fossil fuels and can still achieve good efficiency is the mix of energy. So, blending coal and biomass not only will increase the fusion temperature but will also decrease the slagging and fouling propensity and will ultimately increase the efficiency of boilers.

Ash fusion analysis and fouling and slagging indices help to navigate the fouling and slagging propensity of ash blends. Ash fusion analysis not only helps us to find the fusion temperature of ash blends but also gives the values of initial deformation temperature (IDT) and hemispherical temperature (HT) which can be used to find the ash fusibility index that shows the slagging propensity in blends. For ash blends, XRF determines the elemental composition, and the percentage of metal oxide is determined by this analysis which can be used in slagging and fouling indices to evaluate fouling and slagging propensities.

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Chapter 3 Material and Methods

3.1 Materials Preparation

The sample of CFA was provided by Fauji Power Company Limited (FPCL). Bituminous coal was used to make the standard CFA, and then ground and sieved to reduce its size to less than 0.2 mm. Biomass fly and bottom ash samples were provided by Biomass fired Power Plant Bulleh Shah Packaging Pakistan[1]. Biomass used has a composition of mixed ash feed. It contains rice straw, wooden packaging, wheat straw, corn stalks, and the paper industry's black liquor. BFA was ground and sieved to less than 0.2 mm in size. Then the ash samples were placed in an oven at 130°C for five hours to eliminate moisture. After that, the blends of BFA and CFA were prepared. Three different blends of different ratios were prepared based on their weight. Firstly, the samples of BFA and CFA were ground and sieved to less than 0.2 mm in size and then mixed in a weight-to-weight ratio i.e., the first sample was prepared in a (75CFA + 25BFA) ratio. Second sample prepared has a (50CFA + 50BFA) ratio. The ratio of the third sample prepared is (25CFA + 75BFA) as shown in [Fig. 3.1](#)

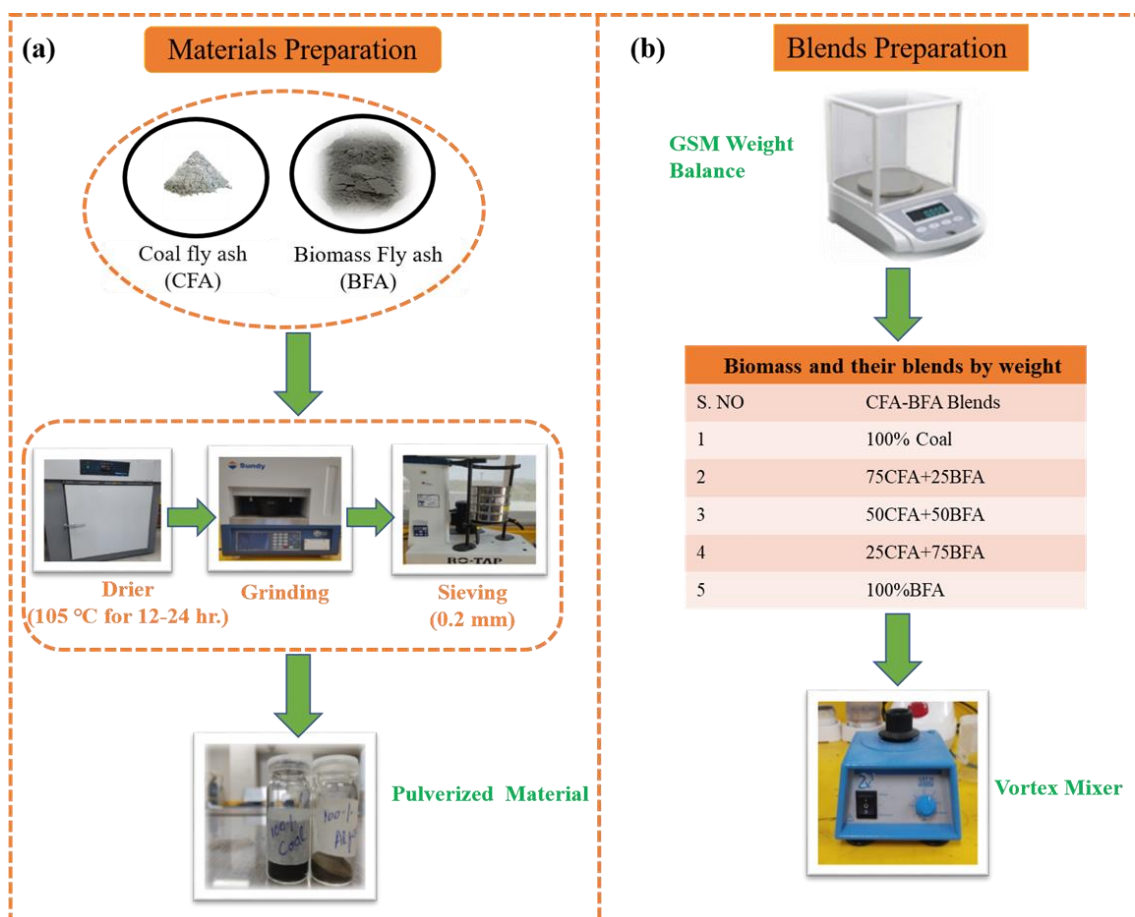


Fig. 3.1 Pure and Blend ash sample preparation (a) Pure samples (b) Blend samples

3.2 Characterization

Using Elemental Analyzer (CKIC 5E- CHN2200, China), the ultimate analysis is performed to analyze Carbon, Hydrogen, and Nitrogen percentages in the Pure and blended ash samples. Samples of CFA, BFA, BBA, and blends of BFA and CFA having a particle size of 0.2 mm and a weight of 80 mg were collected in the aluminum crucible. Carbon, hydrogen, and nitrogen in the ash samples were calculated. The experiments were done in N, He, and O₂ gas environments.

In the ash samples, several functional groups were determined by the usage of FTIR. The equipment used was Agilent Technologies' Cary 630 FTIR for the FTIR. The transmittance of IR spectra was obtained from a range of 4000 to 650 cm⁻¹ with the 2 cm⁻¹ resolution

The thermal stability of samples of coal and biomass ash blends was determined using TGA 5500 (TA instruments, USA). Nitrogen gas at [50 ml/min] flow rate was used to heat 4mg of ash samples to 900°C. For the experiment 20 °C/min⁻¹ heating ramp was used.

For XRF analysis, Elemental Analyzer (cubiX XRF-2300) was used. Liquid nitrogen at a 20 mL min⁻¹ flow rate was used for analysis.

3.3 Ash fusion analysis

Ash and blend ash samples were ground to make them appropriate for analysis of ash fusion. Hard Grove Grindability Index (HGI) Tester (USA) was used for this purpose. Then sieving of the Ash and blend ash Samples was done using Sieving WS Tyler RX-29-10 (USA).

The size of ash samples obtained was smaller than 0.2 mm the following sieving. Ash and blend ash were then allowed to dry to remove moisture from it. A binder solution of 1g Dextrin and 10 mL deionized water was prepared. Then binder solution was mixed with the ash and blended samples to make a paste. This paste was then pressed into the cone mold for the formation of cone samples which are then placed in ash cone plates which are then inserted in the Ash fusion analyzer chamber.

Ash Fusion Determinator 5E-AF4000 (CKIC, China) was used to analyze ash fusion temperature. The temperature standard used for the analysis was GB/T 219-2008, ISO540-1995(E). Different images were captured of cones of ash and their blends at different temperatures which are deformation, spherical, hemispherical, and flow temperatures using a high-resolution inset camera with the help of integrated 5E-AF4000 software. Ash plates are then placed on a ceramic corundum cup after inserting ash and blending ash cones. They are loaded then on an alundum tube inside the ash fusion chamber. Up to 900 °C, they are heated at a rate of 20 °Cmin⁻¹. The rate of heating is lowered to 5 °C-min⁻¹ after 900 °C. At every 10°C increase in temperature, images were taken by a digital probe that was installed inside the furnace. The experiments were performed in both an oxidation and reduction environment. In reducing the atmosphere, a mixture of CO (60 ± 5) % and CO₂ (40 ± 5) % according to standard GB/T219-2008 were connected to the Ash fusion determinator. The flow of the mixture was set to 350 mL/min. Then deformation, spherical, hemispherical, and flow temperature of all ash samples were analyzed and calculated.

3.4 Slagging and fouling indices

Slagging and fouling properties in coal and biomass ash blends were evaluated from the formulas given below. The values in the table below are obtained from XRF analysis and Sulphur analysis.

Different indices were employed to evaluate the slagging and fouling tendencies in CFA, BFA, and their blends.

The most commonly used index, for this reason, is the base-to-acid ratio ($R_{B/A}$). It usually gives the fouling tendencies in biomass presented in Eq. (1)[2]:

$$\frac{\mathbf{CaO + MgO + Fe_2O_3 + Na_2O + K_2O}}{\mathbf{Al_2O_3 + TiO_2 + SiO_2}} \quad (1)$$

This index contains the basic compounds on the top of the equation and acidic oxides on the bottom. The melting point of the ash is increased by acidic oxides, whilst the melting point is decreased by basic compounds. The slagging index is used to calculate the slagging potential in biomass. This depends on the contents of Sulphur in the ash of biomass and coal and is given in Eq. (2)[3]:

$$\left(\frac{\mathbf{B}}{\mathbf{A}}\right) \times \mathbf{Sd} \quad (2)$$

The fouling index can be used to describe fouling in ashes of biomass and coal more accurately as it shows that fouling is mainly caused by alkaline elements which are presented in Eq. (3)[4]:

$$\left(\frac{\mathbf{B}}{\mathbf{A}}\right) \times (\mathbf{Na_2O + K_2O}) \quad (3)$$

Another method of finding the melting behavior of the ash materials is by ash fusibility Index. This index gives the melting behavior following the temperatures found by ash fusion analysis which are Initial deformation temperature (IDT) and Hemispherical temperature (HT). This index gives the melting behavior in both oxidation and reduction environments. Ash fusibility index is presented in Eq. (4)[5]:

$$\mathbf{AFI} = \frac{\mathbf{4 \times IDT + HT}}{\mathbf{5}} \quad (4)$$

Agglomeration caused by the ash of coal and biomass can be calculated from agglomeration or bed agglomeration index presented in Eq. (5)[6]:

$$\frac{\mathbf{Fe_2O_3}}{\mathbf{K_2O + Na_2O}} \quad (5)$$

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Chapter 4 Results and Discussion

4.1 Characterization of individual CFA and BFA and their blends

4.1.1 Ultimate Analysis (CHN)

Carbon, Hydrogen, Nitrogen, and Sulphur percentages in pure ash and blend ash samples were determined through ultimate analysis. Fig. 4.1(a) shows the carbon percentage of pure and blended ash samples. The carbon percentage in coal fly ash (CFA) was (4.93%). In BBA it shows the most carbon percentage which was (17.8%) because of unburnt organic matter. This is also because the boiler did not achieve the desired fusion temperature. The percentage of carbon in BFA was (2.4%). Now in blend samples, the sample which shows the most carbon percentage is the blend which was (25CFA+75BFA). The carbon percentage it contains was (4.94%). The sample which shows the least percentage of carbon was (50CFA+50BFA). In this sample, the carbon percentage was (0.6%). Carbon percentage present in 75CFA+25BFAs was (4.67%). There was a negligible percentage of nitrogen and hydrogen observed in the samples as shown in Fig. 4.1(b). The Sulphur contents in different ash and blend ash samples are given in Fig. 4.1(c). BFA shows the most Sulphur contents which was (4.4%) and the least amount of Sulphur detected in BBA which was (0.9%). The growing conditions and origin of biomass influenced their Sulphur contents. The Sulphur contents in the first blend which is (75CFA+25BFA) contain the most Sulphur contents which were (2.97%). The least amount of Sulphur contents are present in the third blend (25CFA+75BFA) which was (2.92%). The blend (50CFA+50BFA) contained Sulphur contents of (2.94%).

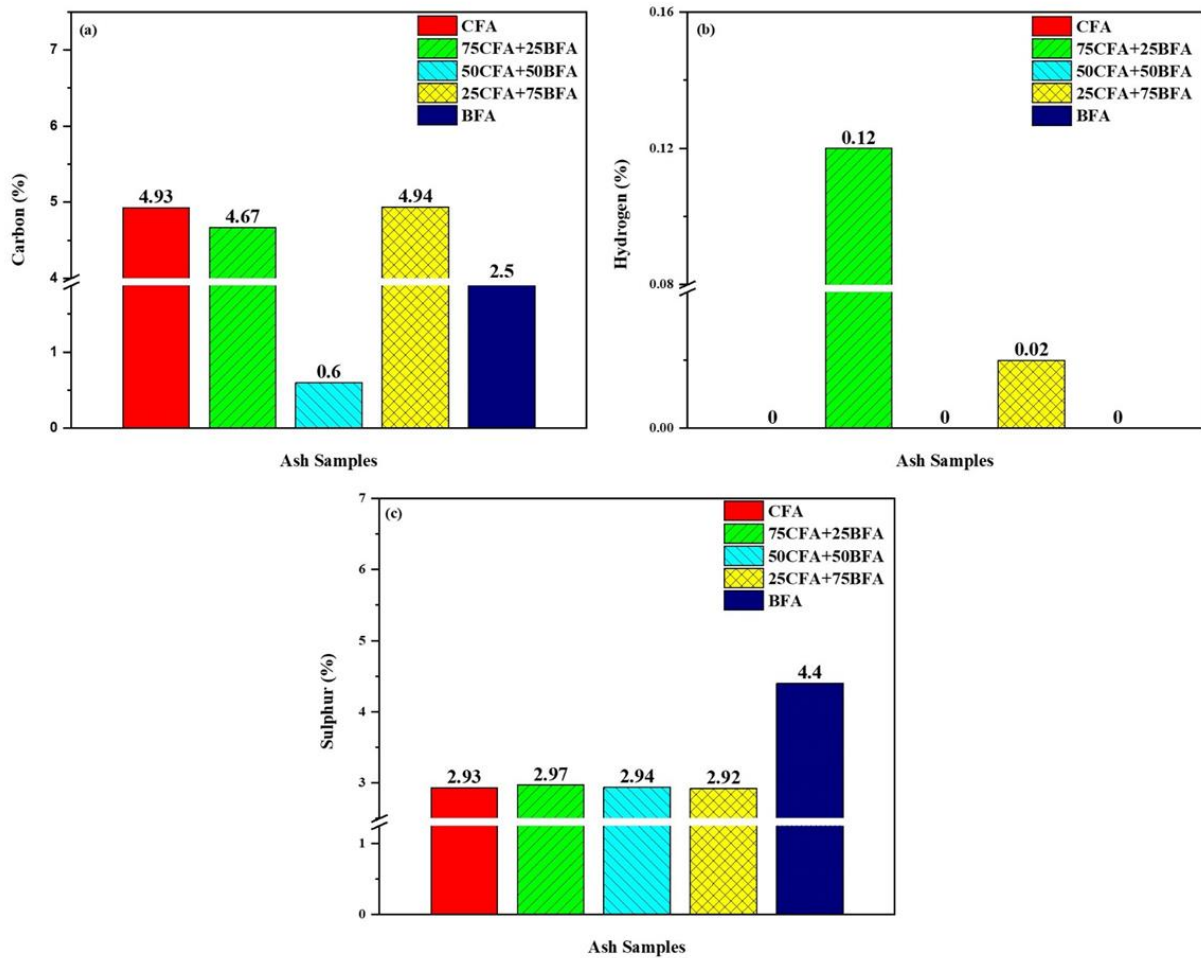


Fig. 4.1 CHN-S of pure and blended ash samples

4.1.2 Thermo-gravimetric analysis (TGA)

Thermal stability of pure and blend ash samples was found by TGA DTH-60H to find the weight loss and moisture removal in these samples following different temperatures. The TGA curve obtained was separated into three phases. Up to 200 °C in Pure and blended ash samples moisture was removed. Then in a later phase weight loss was noticed in ash samples. The oxidation of organic materials happens in this part of the curve, which was up to 600 °C. The final part of the curve explains the reaction and transfer of inorganic matter [1]. In Fig. 4.2(a), from the temperature of 30 °C to 300 °C, there was very low mass reduction and during this range, there is also moisture removal from CFA. The coal fly ash residue was next burned at temperatures ranging from 300 °C-900 °C, resulting in a larger mass reduction in the coal fly ash. The total mass loss during the thermogravimetric analysis of CFA was (3.7%). In Fig. 4.2(b), from the temperature of

20 °C to 200 °C there was moisture removal in the sample (75CFA+25BFA). In this graph also there was very low mass reduction up to 200 °C. Then from 200 °C to 900 °C, there was a substantial mass reduction in the ash sample of (75CFA+25BFA). The total mass loss in the thermogravimetric analysis of the sample (75CFA+25BFA) was (13%). In Fig. 4.2(c), the graph of the sample (50CFA+50BFA) is shown. In this graph, there was moisture removal from 20 °C to 300 °C. There was a very low mass reduction in this range which is shown in the graph. Then from 300 °C to 900 °C, there was a greater mass reduction in the sample. Total mass loss which is found from thermogravimetric analysis of the sample (50CFA+50BFA) was (17%). In Fig. 4.2(d), the graph of the sample (25CFA+75BFA) is shown in which from 20 °C to 300 °C there was no substantial mass loss, but it only shows the moisture removal. Then from 300 °C to 900 °C, there was a substantial mass loss shown and there is moisture removal during this range. The total mass loss shown in this graph was (14%).

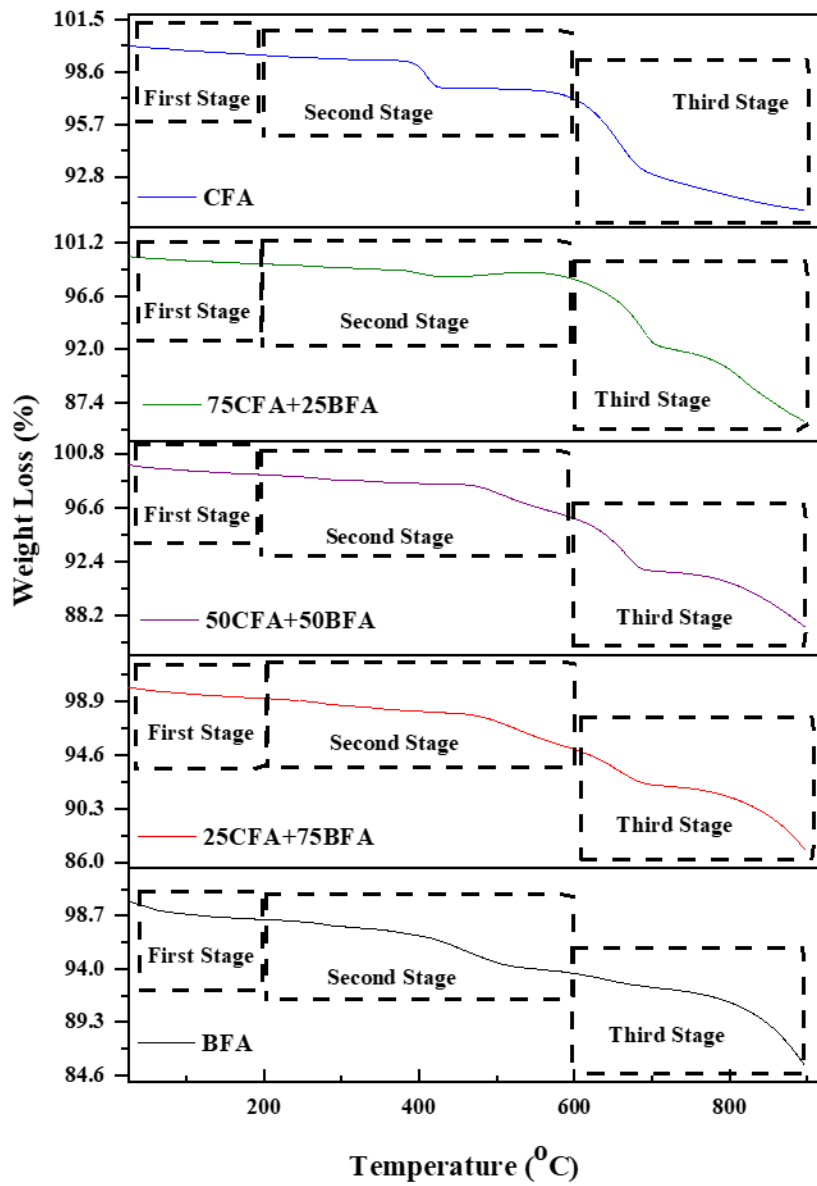


Fig. 4.2 TGA of pure and blended ash samples

4.1.3 Fourier transform infrared spectroscopy (FTIR)

Fig. 4.3 shows the FTIR of BFA, BBA, CFA, and the blends of fly ashes of biomass and coal of different ratios. This reveals the standard appearance of CFA, BFA, and the blends of coal and biomass fly ash bands in relevance to vibrations [2]. In BFA, CFA, (75CFA+25BFA), (50CFA+50BFA), and (25CFA+75BFA) there was a major peak that had the wave number of (1110 cm^{-1}) which shows the presence of Si-O having stretching vibrations[2]. In CFA, BFA, (75CFA+25BFA), (50CFA+50BFA) and (25CFA+75BFA) there was throughout a spectral band at (1420cm^{-1} and 880 cm^{-1}) because of asymmetrical distinct tensile vibrations of C=O. So, in all ash samples, this shows the occurrence of carbonate compounds.[2, 3]. In CFA, (75CFA+25BFA), (50CFA+50BFA) and (25CFA+75BFA), there was a peak of band at (678cm^{-1})which shows the

presence of anhydrate calcium sulphate [3]. There is no OH group present in the spectrum indicating that no moisture is present in the Pure and blended ash samples[4, 5].

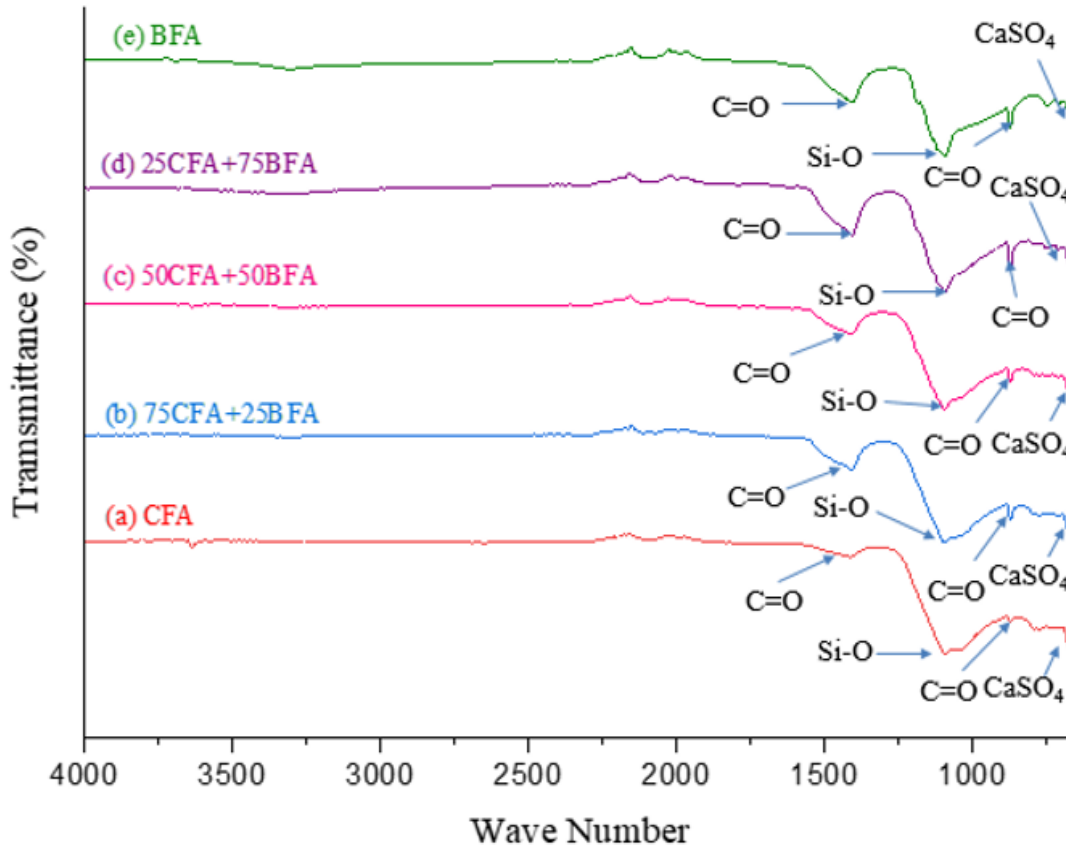


Fig. 4.3 FTIR of pure and blended ash samples

4.2 Ash Fusion Analysis

The ash fusion temperature in all ash samples was examined by the ash fusion determinator. The variation in height of the cone relative to the given temperature was investigated in this study. Fig. 4.4 Shows the fusion temperatures of pure and blended ash in an oxidation environment while Fig. 4.5 show the fusion temperatures of pure and blended ashes in a reduction environment. Usually, CFA has a greater fusion temperature than BFA and BBA [6]. The ratio of $\text{SiO}_2/\text{Al}_2\text{O}_3$ plays an important role in having a high or a low ash fusion temperature. As CFA has a lower $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio than BFA and BBA so, it has a higher ash fusion temperature [7-9]. The structure and composition of ashes up to the original temperature (OT) were unchanged so it was almost the

same for all the samples as it is widely known. As the temperature rises, mass loss begins almost immediately after 930° C. The heating rate at this point is 5 °Cmin⁻¹. In an oxidation environment, CFA had a high deformation temperature (DT) of 1259 °C which is due to the fusion of silicates and aluminates that causes ash fusion temperature to increase[10]. After DT, firstly carbonates start melting and then evaporating till spherical temperature (ST) at 1278 °C was reached[9]. In the case of hemispherical temperature(HT), high melting oxides were further evaporated and are completely oxidized as all elements at this point were liquefied [11].

As biomass used has an alkaline nature, there exist some eutectic compounds in biomass. Fusion temperature is low as metal oxides and silicates are present in the biomass [11]. The difference in temperature in biomass ashes is low. The difference in temperature in the sample of ashes of biomass was observed. The OT temperature for both BFA and BBA were similar which was 928 °C. The DT for BFA was 1178 °C while for BBA it was 1176 °C. The presence of K₂O was the reason because the DT of BFA was greater than BBA [11]. Upon reaching DT, ash samples of biomass shrunk due to reduced surface area.

Low melting composites were generated due to the presence of SiO₂ in high content due to their reaction with alkali oxides which is shown in the XRF[12]. Biomass ashes rapidly condensed due to very low differences in their melting temperatures which causes them to easily deposit on heating surfaces. The DT of BFA was greater due to the presence of Al₂O₃ [13]. There was a change in morphology due to the evaporation of carbonates in ST (1191 °C) and HT (1194 °C) [11]. The area of the cone was increased when it reaches the flow temperature FT of 1197 °C [10]. In the case of BBA, spherical temperature (ST) was greater due presence of MnO and was 1203 °C [11]. Due to the vaporization of carbonates and the melting properties of eutectic compounds, the HT of BBA was 1213 °C [11]. The flow temperature (FT) of BBA was 1215 °C due to the oxidation of all fusing minerals and it causes the area of the cone to increase [10].

In ash blends, the fusion temperature of biomass fly ash is increased due to the presence of coal fly ash. As demonstrated by XRF, the weight percentage of basic oxides is decreased and the weight percentage of acidic oxides like SiO₂ and Al₂O₃ is increased. Now, as it is reported in previous studies, acidic oxides raise the ash fusion temperature whereas basic oxides lower it. [14]. As a result of the increased weight percentage of SiO₂ and Al₂O₃ in these blends, temperature rises.

In reducing atmosphere, fusion temperature is decreased for each sample as in CO/CO₂ atmosphere iron oxide is reduced to FeO which can reduce ash fusion temperature[15].

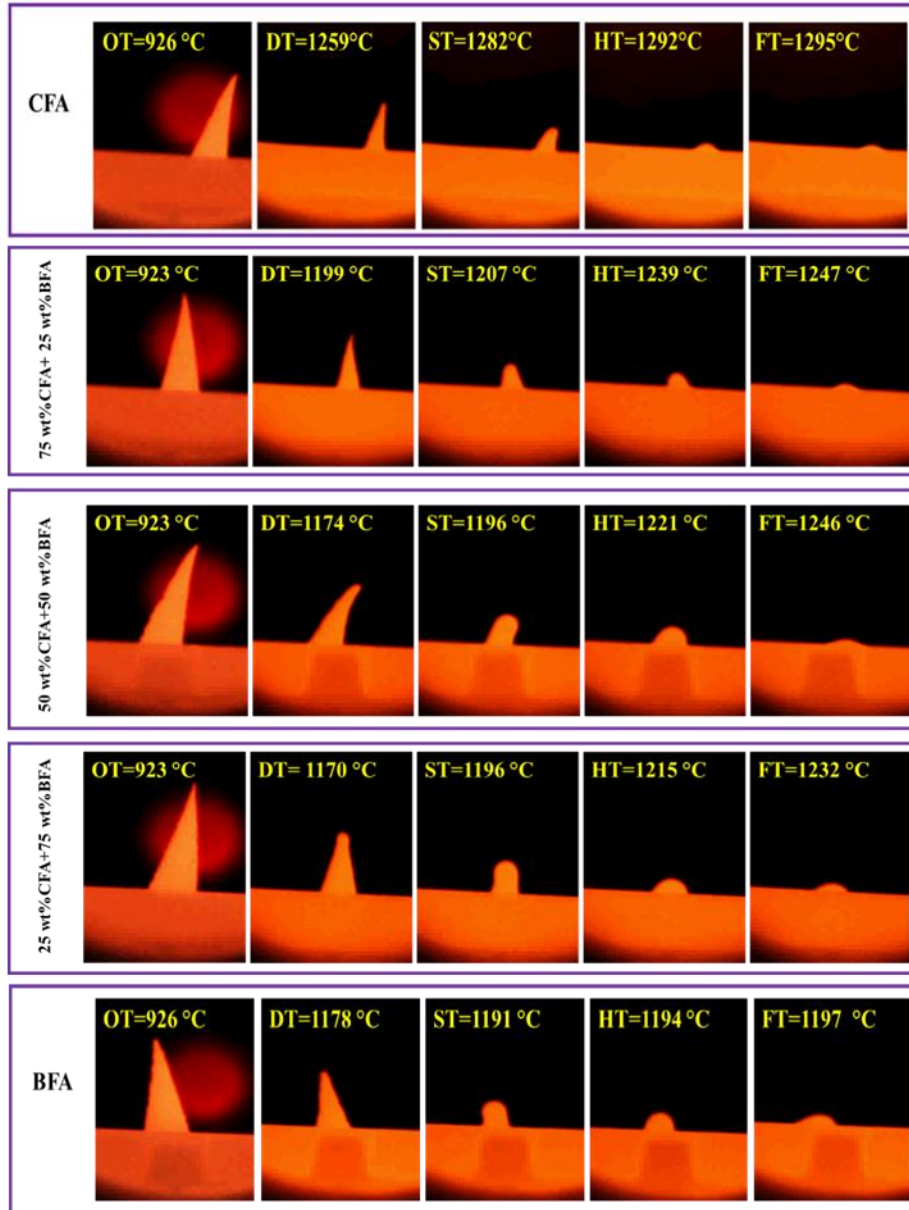


Fig. 4.4 Ash fusion analysis of pure and blended ash samples in an oxidation environment

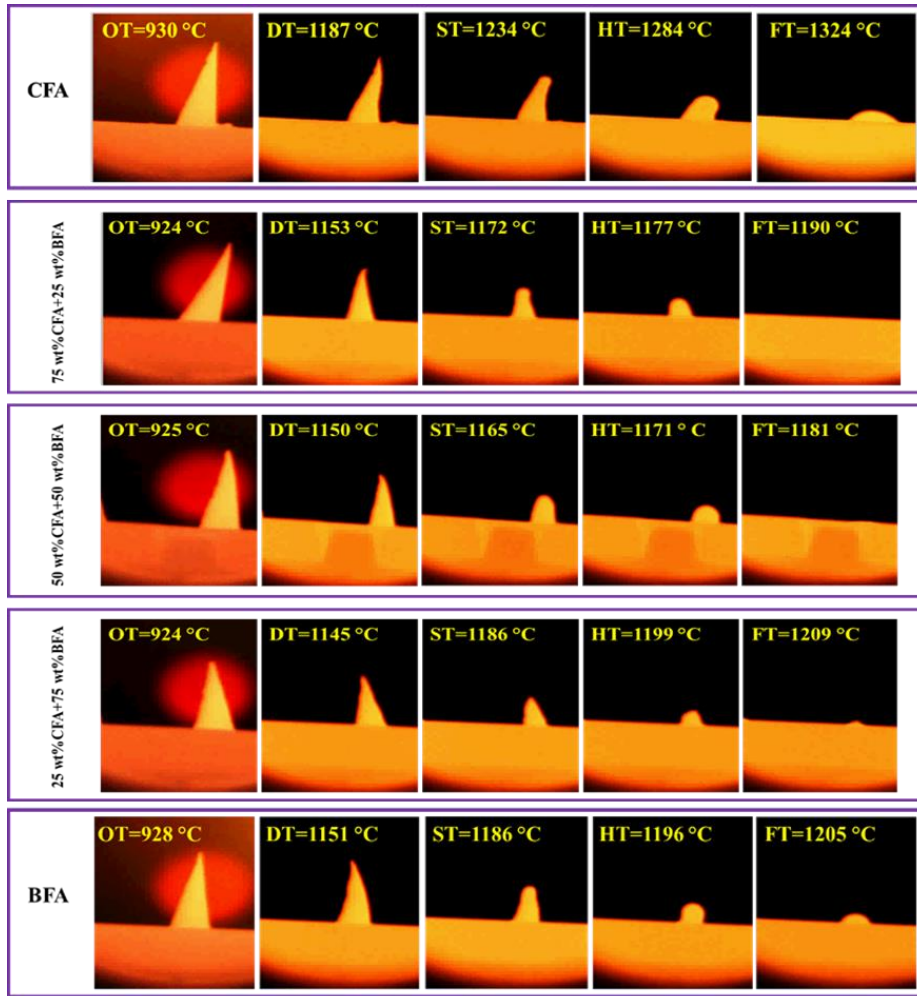


Fig. 4.5 Ash fusion analysis of pure and blended ash samples in a reduction environment

4.2.1 X-Ray fluorescence (XRF)

Many inorganic materials may be found in biomass and coal ash. These are reported in the form of their stable oxides by their weight percentage. The common stable oxides are SiO₂, Fe₂O₃, Al₂O₃, MgO, CaO, K₂O, Na₂O, and TiO₂. The weight percentage of all ash samples is represented in Fig. 4.6.

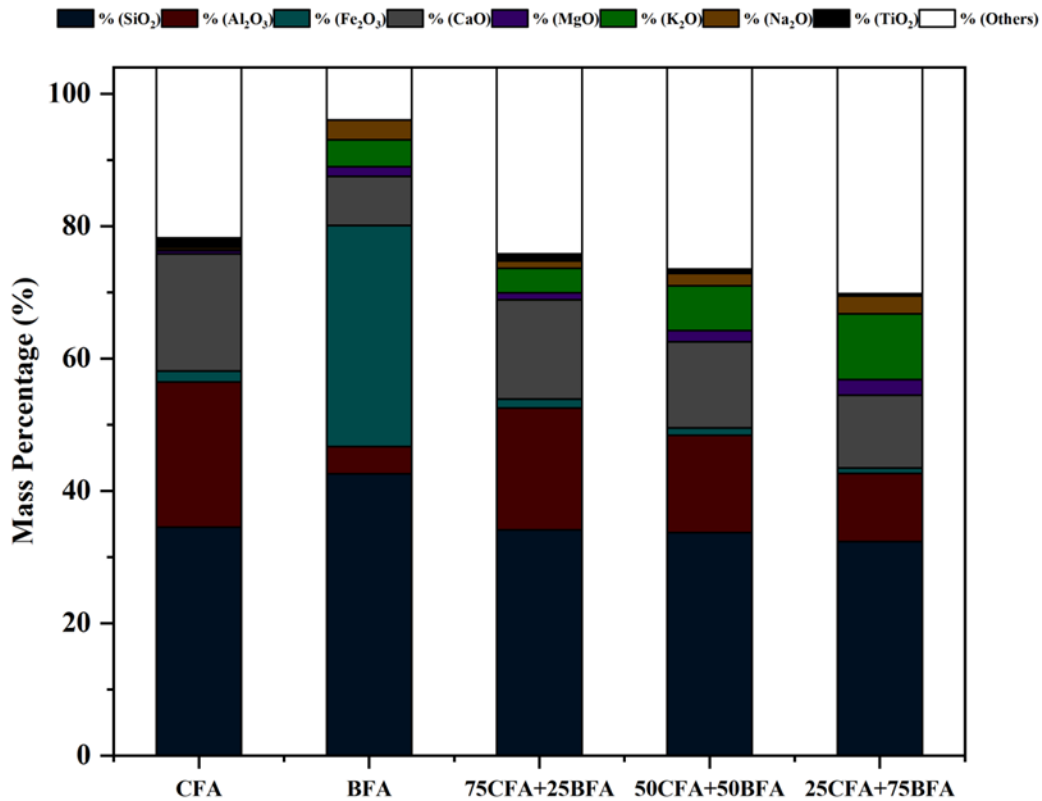


Fig. 4.6 XRF of pure and blended ash samples

Different indices were used to determine the slagging potential of various biomass and coal ashes. Base-to-Acid ratio ($R_{B/A}$) was used to measure the effects of slagging caused by the addition of coal fly ash. Now coal shows low levels of slagging as $R_{B/A}$ was (0.352%) as shown in Table 4.1 [16]. Biomass on the other hand shows high slagging which was (1.055%)[17]. Then different ratios of coal fly ash and biomass fly ash show different slagging effects. The sample (75CFA+25BFA) shows the lowest slagging having $R_{B/A}$ (0.416%) as it contains the maximum amount of coal. All blend samples show that with the addition of coal there is a considerable

reduction in the slagging tendency of biomass. Samples (50CFA+50BFA) and (25CFA+75BFA) shows that slagging tendency will decrease by addition of coal as their $R_{B/A}$ were (0.5%) and (0.625%). This shows that they lie in the range of low slagging potential[17]. The slagging index is another parameter to find the slagging tendency of the fuel used. This depends on the Sulphur content of coal and biomass as shown in Eq. 2. The slagging index of CFA was (0.56%) which lies in the range of low slagging[18]. So, CFA shows a low level of slagging according to this index. BFA had a slagging index of (4.64%) which is in the range of extremely high slagging[18]. When CFA is blended with BFA at different ratios, the slagging propensity in biomass is decreased as indicated in Table 4.1. The slagging index of (75CFA+25BFA) was (1.24%). The slagging index of (50CFA+50BFA) and (25CFA+75BFA) were (1.47%) and (1.71%) respectively. They all lie in the range of medium slagging following the slagging index [18]. So, under this index, the slagging tendency in biomass will decrease with the addition of coal. The sample which is optimum due to a good energy mix will be (50CFA+50BFA).

The fouling tendency in CFA was (0.1936%) which lies in the range of low fouling[19]. The biomass shows a high level of fouling as the value of the fouling index was (7.44%)[19]. The blends also show a high level of fouling as the values of all the blends were (2.022%), (4.34%), and (7.91%) respectively which are in the range of high fouling [19]. So, here optimum sample will be (50CFA+50BFA) because of the good energy mix.

Now the value of bed agglomeration of CFA was (3.02%). So it is likely for CFA to cause bed agglomeration[20]. BFA and (75CFA+25BFA) also show the tendency for bed agglomeration[20]. While in (50CFA+50BFA) and (25CFA+75BFA), there is a low tendency of bed agglomeration [20]. So, the optimum sample will be (50CFA+50BFA).

The samples of CFA had an Ash fusibility index of 1265.4 °C which is in the range of medium slagging [21]. While all the other blends showed high slagging potential in an oxidation environment. While in a reduction environment all samples including CFA showed a high tendency of slagging [21].

Table 4.1 Slagging and Fouling Indices

Fuels	R_{B/A}	R_s	F_u	BAI
CFA (%)	0.352	0.56	0.1936	3.02
BFA (%)	1.055	4.64	7.44	4.73
(75wt%CFA+25wt%BFA)	0.416	1.24	2.022	0.284
(50wt %CFA+50wt%BFA)	0.5	1.47	4.34	0.13
(25wt%CFA+75wt%BFA)	0.625	1.825	7.91	0.065

Table 4.2 Ash Fusibility Index of Pure and Blend Ashes (Reduction Environment)

Ash Samples	Ash Fusibility index (AFI) °C
BFA	1160
BBA	1156.8
CFA	1206.4
75CFA+25BFA	1157.8
50CFA+50BFA	1154.2
25CFA+75BFA	1155.8

Table 4.3 Ash Fusibility Index of Pure and Blend Ashes (Oxidation Environment)

Ash Samples	Ash Fusibility index (AFI) °C
BFA	1181.2
BBA	1183.4
CFA	1265.4
75CFA+25BFA	1189.6
50CFA+50BFA	1173.2
25CFA+75BFA	1177

Summary

The blends of biomass and coal were characterized using CHN, TGA, FTIR, and XRF. CHN analysis investigate the carbon content was increased in BFA by the addition of biomass. There is a negligible amount of nitrogen and hydrogen in ash samples. Sulfur analysis shows that the amount of Sulphur is decreased by the addition of biomass thus reducing SO_x emissions. TGA showed a significant decrease in mass reduction, however, thermal stability was detected when altering with coal. FTIR shows the presence of silicates and carbonates which affect the fusion temperature of ash blends. In XRF, it is shown that the weight percentage of acidic oxides is increased which is the reason for high ash fusion temperature. Ash fusion analysis shows that fusion temperature is increased by the addition of CFA in BFA. (75CFA+25BFA) shows the highest fusion temperature. Base-to Acid Ratio, Slagging index, Fouling Index and Ash fusibility index show that (75CFA+25BFA) shown the lowest slagging and fouling propensities, and bed agglomeration is also decreased by blending of coal and biomass.

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Chapter 5 Conclusions and Recommendations

5.1 Conclusions

The blends of BFA and CFA were investigated by characterization, ash fusion analysis, and fouling and indices to find their fouling and tendencies. The CFA was added to BFA to increase its fusion temperature and to decrease the propensity of fouling and biomass. It was shown that for all three blends, the blend which has shown the greater tendency for the reduction of slagging and fouling was (50CFA+50BFA). As biomass has shown high slagging and fouling potential. While in the blend (50CFA+50BFA), it has mostly shown a low potential of slagging and fouling. So, here optimum sample will be (50CFA+50BFA) because of the good energy mix. As the coal has greater fusion temperature and lowers slagging and fouling potential, it will also reduce the slagging and fouling tendency of biomass.

5.2 Recommendations

The blending of biomass and coal is an efficient and greener way to increase fusion temperature and reduce slagging and fouling. Slagging and fouling in biomass can further be reduced if we blend biomass with another coal whose calorific value is higher. It can further be reduced if we use different percentages of additives of metal oxides which can increase the fusion temperature of biomass. Slagging and fouling occur in different equipment like in rotary dryers in the fertilizer industry and its propensity can also be analyzed using these different indices.