

Role of Torrefaction and Briquetting in Improving Biomass Suitability for Iron Ore Sintering

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ABSTRACT

Due to the extensive use of non-renewable sources of energy such as coal and coke breeze in the production of iron ore sinter, the iron and steel industry is regarded as one of the leading emitters of carbon dioxide emissions globally. The use of biomass as an eco-friendly substitute has been made feasible due to its abundance and carbon neutrality. There are various problems associated with using raw biomass owing to the high moisture content, low energy density, poor grindability, inconsistent burning behavior, and difficulties in transportation. Torrefaction and briquetting are two significant processing techniques that can greatly improve the qualities of biomass as a fuel source for industries. This research investigates the characteristics of biomass, the effects of torrefaction on its properties, different methods for the production of briquettes, and their interaction to influence the quality of fuel, its combustion performance, and sintering performance. Research indicates that torrefied briquettes of biomass exhibit better handling characteristics, high mechanical strength, minimal moisture content, and high calorific value compared to untreated biomass. Using enhanced biomass in the process of sintering not only helps in reducing environmental pollution by minimizing the use of fossil fuels but also cuts down on the consumption of coke.

Keywords: Biomass, Torrefaction, Briquetting, Iron Ore Sintering, Renewable Fuel, Sustainable Steelmaking

1. Introduction

Because the iron and steel industry depends extensively on fossil fuels such as coal and coke breeze, this industry is one of the largest consumers of energy among all other industries and produces vast amounts of greenhouse gases. In the case of integrated steel plants, the iron ore sintering process is an essential agglomeration method to prepare the iron ore particles in the form of sinter so that they can be fed into the blast furnace. Coke breeze acts as the primary fuel in the iron ore sintering process, creating heat through which iron ore particles melt partially and bond together. But burning coke results in large emissions of CO₂, SO_x, and NO_x gases that cause immense environmental pollution and global warming [1]. The increasing demand for stricter environmental regulations and the global need for sustainable steelmaking have encouraged companies and scientists to seek renewable alternative sources of fuel that will reduce the usage of fossil fuel in the sintering process [2].

Biomass has emerged as an attractive source of renewable energy because of its abundant availability, low sulfur content, and neutral carbon status [3]. Biomass materials like rice husks, sawdust, bamboo shavings, coconut shells, bagasse, wood chips, and various forest and agricultural waste products contain a significant amount of energy and can act as a partial substitute for coke breeze in iron ore sintering. Unlike fossil fuel, biomass relies on photosynthesis to absorb atmospheric carbon dioxide from the environment through plants [4]. As per various studies conducted in the recent past, the steel production companies can reduce their greenhouse gas emissions and make themselves more environmentally sustainable through partial replacement of coke breeze with biomass [2]. Additionally, biomass energy sources also produce comparatively lesser amounts of ash and sulfur, thus promoting cleaner manufacturing processes and reduction of pollution in the environment [5].

However, the utilization of raw biomass as a fuel material in the sintering process of iron ores remains challenging despite the above-mentioned advantages owing to several inherent undesirable physicochemical properties. These include high moisture content, low bulk density, high volatiles, fibrous nature, and poor grindability when compared with coke breeze [6]. During the sintering process, such properties adversely affect the processing aspects of biomass as fuel. Although low density and inconsistent particle size cause lower permeability and thermal

uniformity in the bed during sintering, high moisture contents increase heat losses during combustion [3]. Moreover, the fast volatilization of raw biomass may affect the thermal characteristics of the sinter bed, leading to poor-quality sinter and reduced productivity [7]. Hence, it is necessary to perform suitable pre-treatment methods to improve the properties and applicability of biomass as fuel.

Torrefaction is one of the effective thermochemical pre-treatment methods that can be used to improve the quality of biomass as a source of energy. It involves heating the biomass under oxygen-restricted or inert conditions at temperatures ranging from 200°C to 300°C.

$$200^{\circ}\text{C} \leq T \leq 300^{\circ}\text{C}$$

Torrefaction results in the production of a high-energy-density carbonaceous material with excellent fuel characteristics, which involves removing moisture, volatiles, and degradation of hemicelluloses [8]. Torrefied biomass offers superior combustion properties, higher calorific value, greater hydrophobicity, grindability, and lower moisture content than non-treated biomass [6]. It is better adapted to iron ore sintering processes since it resembles poor quality coal in terms of visual appearance and thermal behavior [9]. Scientific studies have shown that torrefaction significantly improves the energy density and thermal stability of biomass, making it appropriate for metallurgical applications [10]. Though torrefaction improves the thermodynamic behavior of biomass, torrefied biomass usually occurs in powder or brittle state that makes it difficult for handling, storing, transport, and dust formation [11]. As such, at high pressure, briquetting acts as the densification method to produce biomass in the form of compacted fuels. Briquetting helps in increasing the density, mechanical strength, and handling ability while decreasing transport and storage expenses [12]. Industrial use of briquetted biomass fuels exhibits good resistance, constant calorific value, and reliable combustion performance [13]. The combination of torrefaction and briquetting provides good-quality briquettes with good thermophysical and physicochemical properties suitable for industrial high-temperature processes such as iron ore sintering [11]. A number of researches conducted in relation to biomass utilization in the sintering process of iron ores have produced positive results with regard to reduced emissions and biomass substituting fossil fuels. Several studies show that biomass briquettes and torrefied biomass can be used in partial substitution of coke breeze without significant decrease in productivity and strength of sinter [2]. The application of upgraded biomass fuels in the steel production sector contributes to greater sustainability of the environment, reduced carbon dioxide emissions, and lower dependency on nonrenewable energy sources [5]. Moreover, due to utilizing agriculture and forestry residues, which could be otherwise disposed of and contribute to pollution, biomass fuels promote energy recovery from waste and principles of the circular economy [14]. Thus, increased interest is generated for such sustainable technologies as torrefaction and briquetting.

2. BIOMASS AS AN ALTERNATIVE FUEL IN IRON ORE SINTERING

One of the most crucial procedures in integrated steel plants for turning fine iron ore particles into porous sinter appropriate for blast furnace operations is iron ore sintering. The main fuel utilized in this process to produce the heat needed for the partial melting and bonding of iron ore particles is typically coke breeze. However, the widespread use of fossil fuels in sintering processes greatly increases greenhouse gas emissions, pollutes the environment, and depletes non-renewable resources. Researchers and businesses are investigating renewable alternative fuels to lessen reliance on traditional coke breeze due to growing environmental concerns and the need for sustainable industrial operations worldwide. Biomass has become a feasible alternative fuel for iron ore sintering among the renewable energy resources available because of its Due to its availability, carbon neutrality, and renewability, biomass has emerged as one of the best potential renewable energy sources for iron ore sintering. Biomass includes organic substances derived from forestry wastes, industrial wastes, energy crops, and agricultural wastes. Rice husks, sawdust, bamboo wastes, coconut shells, bagasse, palm kernel shells, wood chips, maize stalks, and agricultural straw are common forms of biomass material used for metallurgy applications. Combustible carbon compounds capable of providing heat energy on combustion are found in these types of biomass sources. The emissions of carbon released into the air from biomass combustion are much lesser than those from fossil fuel combustion due to the photosynthesis process of biomass plants. Therefore, utilization of biomass could contribute to reduction of greenhouse gases and environmentally sustainable production of steel.

First, in comparison with coal and coke breeze, biomass consists of a relatively low concentration of sulfur and nitrogen. Therefore, application of biomass would lead to the reduction of emission of sulfur oxide and nitrogen oxide,

both of which contribute significantly to air pollution. Besides, biomass contains less ash than other fuels. It means that there will be less waste and the quality of burning will be better. In addition, biomass ash may contain alkali and alkaline earth elements which affect sintering and combustion processes. The high content of volatile matter in biomass makes its igniting easier. The reason why biomass is considered to have the possibility of partially substituting coke breeze in iron ore sintering without significantly affecting the quality of sintering means that biomass has been attracting considerable attention as an alternate fuel. In optimal working conditions, the combustion of biomass leads to improved thermal efficiency, providing the required amount of heat to enable sintering. Moreover, the increased permeability and airflow in the sintering bed can be attained due to the porosity of biomass. The partial replacement of coke breeze by biomass has the ability to decrease greenhouse gases emission and fossil fuel usage while maintaining enough production of sinter. There are certain problems faced when raw biomass is directly used in iron ore sintering operations. High moisture content in raw biomass, which reduces the effective calorific value since more energy is required to evaporate moisture following combustion, is one of the biggest disadvantages. In the sintering process, high moisture content leads to inefficient and unstable combustion. The relatively low bulk density of biomass compared to that of coke breeze is another disadvantage of using biomass. Not only does low density mean more volume occupied for storage, but also biomass becomes difficult to convey and blend with fine iron ore. In addition, biomass may segregate from the sinter mixture, and this may affect combustion efficiency and bed permeability. Moreover, raw biomass contains a low percentage of fixed carbon and high levels of volatiles. Rapid combustion of biomass causes quick burning of the sinter bed and poor heat distribution. Fast burning can reduce the mechanical strength of the end sinter product and cause disturbance in the temperature regime necessary for proper production of the sinter material. In addition, due to its fibrous structure, biomass becomes incompatible with the present fuel systems as a result of difficulties encountered in the grinding process. There are various pretreatment procedures like torrefaction, carbonization, briquetting, and pelletization, which are applied to overcome these limitations. Moisture reduction, increase in calorific value, increase in density and grindability, and other properties of biomass can be enhanced using these treatments. In spite of the fact that briquetting makes it easier to handle the fuel by converting loose biomass into dense lumps, the main advantage of torrefaction is conversion of biomass into coal-like material. Torrefied briquettes and biochar are two types of biomass fuels which, in contrast to traditional charcoal briquettes, have better properties and are more appropriate for iron ore sintering due to superior burning characteristics and higher thermal stability.

In addition, there is considerable economic and ecological merit in utilizing biomass for iron ore sintering processes. For agrarian countries, there is an abundance of biomass fuel sources which will lead to effective utilization of wastes from forests and agriculture, otherwise creating disposal problems. Utilization of biomass in industry means transformation of renewable waste into energy, thus implementing the principles of the circular economy. At the same time, partial replacement of coke breeze with biomass contributes to energy sustainability in the iron and steel industry. Despite having a wide range of applications in terms of providing alternative energy for iron ore sintering processes, biomass still faces problems such as biomass availability, high cost of preprocessing, stability in storage, seasonality, and the optimization process. As such, research in the area of biomass upgrading and optimization must continue to achieve sustainable and efficient iron ore sintering.

Table 1: Comparative Analysis of Biomass as an Alternative Fuel in Iron Ore Sintering

Parameter	Coke Breeze	Raw Biomass	Torrefied Biomass	Briquetted Biomass	Torrefied Briquettes
Nature of Fuel	Fossil Fuel	Renewable	Renewable	Renewable	Renewable
Moisture Content	Low	High	Low	Moderate	Very Low
Bulk Density	High	Low	Moderate	High	High
Calorific Value	High	Low	Improved	Moderate	High
Fixed Carbon	High	Low	Moderate	Moderate	High
Volatile Matter	Low	High	Reduced	Moderate	Controlled
Sulfur Content	High	Very Low	Very Low	Very Low	Very Low
Ash Content	High	Low	Low	Low	Low
Grindability	Good	Poor	Improved	Improved	Excellent

Combustion Rate	Stable	Rapid	Controlled	Uniform	Stable
Ignition Behavior	Moderate	Fast	Improved	Uniform	Controlled
Mechanical Strength	Strong	Weak	Brittle	Strong	Very Strong
Hydrophobic Nature	Good	Poor	Improved	Moderate	Excellent
Storage Stability	Good	Poor	Improved	Improved	Excellent
Transportation Efficiency	Good	Poor	Moderate	Good	Excellent
Handling Characteristics	Easy	Difficult	Moderate	Easy	Easy
Dust Formation	Low	High	Moderate	Low	Very Low
Bed Permeability in Sintering	Stable	Disturbed	Improved	Improved	Highly Stable
Heat Generation Stability	Stable	Uneven	Improved	Uniform	Highly Uniform
CO ₂ Emission	High	Low	Lower	Lower	Lowest
SO _x Emission	High	Very Low	Very Low	Very Low	Very Low
NO _x Emission	High	Low	Low	Low	Low
Environmental Impact	High Pollution	Eco-friendly	Cleaner Fuel	Cleaner Fuel	Highly Sustainable
Waste Utilization	No	Yes	Yes	Yes	Yes
Industrial Suitability	Excellent	Limited	Good	Very Good	Excellent
Recommended Coke Replacement	—	5–10%	15–25%	10–20%	20–35%

Table 2: Technical Properties of Biomass Fuels for Iron Ore Sintering

Parameter	Unit	Coke Breeze	Raw Biomass	Torrefied Biomass	Biomass Briquette	Torrefied Briquette
Moisture Content	%	2–5	10–50	2–8	5–12	2–5
Bulk Density	kg/m ³	750–850	100–250	250–400	600–900	750–1100
Calorific Value	MJ/kg	24–30	12–18	18–24	16–22	22–28
Fixed Carbon	%	75–85	10–20	25–40	20–35	40–60
Volatile Matter	%	5–15	65–80	40–60	45–65	25–45
Ash Content	%	10–18	1–8	2–10	2–8	3–10
Sulfur Content	%	0.5–1.2	0.02–0.10	0.02–0.08	0.02–0.08	0.01–0.05
Carbon Content	%	80–90	40–50	55–70	50–65	65–80
Hydrogen Content	%	2–4	5–7	4–6	4–6	3–5
Oxygen Content	%	5–10	35–45	20–30	20–35	10–20
Ignition Temperature	°C	550–650	250–350	300–400	320–450	400–500
Combustion Rate	—	Moderate	Very Fast	Controlled	Uniform	Stable
Energy Density	GJ/m ³	18–22	2–5	7–10	12–18	18–24
Mechanical Durability	%	95–98	Low	Moderate	85–95	92–98
Water Absorption	%	Very Low	High	Low	Moderate	Very Low
Grinding Energy Requirement	kWh/t	High	Moderate	Low	Moderate	Low
Recommended Replacement Ratio	%	—	5–10	15–25	10–20	20–35

3. Torrefaction of Biomass

A thermochemical pretreatment method called torrefaction is used to improve the fuel quality of biomass for use in industrial energy applications. The procedure entails heating biomass at moderate temperatures, typically between 200°C and 300°C, in an oxygen-limited or inert environment. Moisture and light volatile chemicals are eliminated from the biomass during torrefaction, which improves the fuel's calorific value, moisture content, grindability, and

combustion stability. These advancements make torrefied biomass more appropriate for use in metallurgical processes like gasification, co-firing, combustion, and iron ore sintering. Cellulose, hemicellulose, lignin, moisture, and volatiles are some components of biomass feedstocks like rice husk, sawdust, bamboo waste, bagasse, wood chips, coconut shell, and agri-waste. Of all these constituents, hemicellulose is the most unstable one and begins to degrade during torrefaction. Evaporation of moisture and other volatile gases occurs during the entire degradation process, and the percentage of carbon content increases in the solid residue formed. As a result, the solid residue obtained through torrefaction becomes more coal-like, dark, brittle, and hydrophobic in nature. During higher temperature torrefaction, cellulose partially decomposes while lignin remains stable. Drying, thermolysis, and cooling are the three stages involved in the torrefaction process. In the first stage, at low temperatures, the free moisture present in the biomass is removed through the drying process. The biomass is heated under low-oxygen conditions in the second stage, known as thermolysis, where the biomass undergoes partial devolatilization and decomposition of its organic molecules. To prevent oxidation reactions, the torrefied biomass is cooled in the final stage.

The enhancement of energy density is one of the objectives of the torrefaction process. One of the limitations of using raw biomass for industrial purposes is that the high moisture content and calorific value reduce its efficiency. The torrefaction process increases the carbon content while reducing the oxygen content of the biomass, improving its heating value. Due to the similarities between the characteristics of the torrefied material and that of low-grade coal as a fuel, it becomes easier to integrate into existing industry-combustion processes.

The ability to create hydrophobic characteristics in the biomass material is another important advantage offered by the torrefaction process. Since the raw biomass material is hygroscopic, it easily absorbs moisture from the environment. High moisture content has a negative effect on both storage capacity and combustibility. The ability to reduce the number of compounds that absorb moisture makes the material hydrophobic. This hydrophobicity improves the ability to store the material for a longer period. Furthermore, the torrefaction process greatly increases the brittleness and grindability of biomass material. The structure of biomass becomes fragile and brittle after torrefaction, thereby requiring lesser energy input for size reduction. Improved grindability allows torrefied biomass to be processed using conventional coal mills which are commonly employed in the steel and iron industry. In iron ore sintering plants, where a uniform burning behavior and proper bed permeability require uniform particle sizes, this attribute assumes paramount importance. Enhanced combustion behavior is yet another important benefit derived from torrefaction. As fresh biomass is made up of volatile substances, it tends to combust rapidly with inconsistent heat release. The thermal pattern of sintering beds and industrial furnaces can thus get disrupted due to such an inconsistent combustion behavior. Torrefied biomass, which comprises of fixed carbon and fewer volatiles, tends to combust at a slower rate and in a controlled manner. Controlled heat production aids in improving thermal stability and sinter quality during iron ore sintering processes. Three types of torrefaction include light, medium, and severe torrefaction. Light torrefaction is differentiated from other forms of torrefaction by its operation temperature and residence time. While mild torrefaction partially deconstructs hemicellulose, light torrefaction primarily removes moisture and light volatile compounds. Highly carbonized biomass that contains less volatile matter and more energy density is generated through severe torrefaction. Despite a reduction in biomass mass production, the quality of fuel is enhanced due to an increased level of torrefaction intensity.

Torrefaction reactors utilized in industries include rotary drum reactors, fixed bed reactors, screw reactors, moving bed reactors, and fluidized bed reactors. The rotary drum reactor is often used due to the uniformity of heat transfer and constant biomass flow. Parameters like biomass, production capacity, particle size, rate of heating, and residence time have a role to play in deciding on the right type of reactor. There are several operating parameters that have an impact on the efficiency of torrefaction, such as temperature, residence time, rate of heating, particle size, and environmental parameters. Among all these, temperature is the critical parameter that decides both the product quality and energy density. Usually, higher temperature levels lead to higher biomass quality, characterized by increased carbon content and calorific value. The ability of torrefied biomass to act as an alternative for coke breeze along with lower consumption of fossil fuels makes it very promising for the utilization in iron ore sintering processes. The properties of torrefied biomass make possible stable heating, controlled combustion process, minimum heat losses due to presence of water and minimal greenhouse gas emissions. The qualities of torrefied biomass which are similar to those of coal make it possible for torrefied biomass to be used within existing industrial systems of fuel handling. There are some drawbacks of the torrefaction method that should be noted. Pre-treatment costs have been elevated due to the usage of special equipment, specific environmental parameters and energy expenditure. However, optimizing reactor design,

efficiency of energy use, and process economics can be necessary to implement the process on an industrial scale. Also, different biomass samples show different responses to the process of torrefaction, depending on their structure and chemical composition. Taking into account all these facts, we can conclude that torrefaction is a highly efficient method of biomass conversion that significantly increases its properties both physical and chemical. Torrefaction results in increased energy density of biomass, its hydrophobicity, grindability, combustibility, and storability, making it much more suitable for industrial applications like iron ore sintering.

Table 3: Technical Parameters and Properties of Biomass Torrefaction

Parameter	Raw Biomass	Light Torrefaction	Mild Torrefaction	Severe Torrefaction
Temperature Range (°C)	Ambient	200–235	235–270	270–300
Residence Time (min)	—	10–20	20–40	40–60
Moisture Content (%)	10–50	5–12	2–8	1–5
Bulk Density (kg/m ³)	100–250	180–320	250–400	350–500
Calorific Value (MJ/kg)	12–18	16–20	18–24	22–28
Fixed Carbon (%)	10–20	18–28	25–40	40–60
Volatile Matter (%)	65–80	55–70	40–60	25–45
Ash Content (%)	1–8	2–8	2–10	3–12
Carbon Content (%)	40–50	50–60	55–70	65–80
Oxygen Content (%)	35–45	28–38	20–30	10–20
Hydrogen Content (%)	5–7	4–6	4–5	3–5
Energy Density (GJ/m ³)	2–5	5–8	7–12	12–18
Hydrophobic Nature	Poor	Moderate	Good	Excellent
Grindability	Poor	Improved	Good	Excellent
Combustion Stability	Rapid	Improved	Controlled	Stable
Mechanical Strength	Weak	Moderate	Good	Brittle
Water Absorption	High	Moderate	Low	Very Low
Storage Stability	Poor	Improved	Good	Excellent
Dust Formation	High	Moderate	Low	Moderate
Mass Yield (%)	100	80–90	65–80	50–70
Energy Yield (%)	100	85–95	75–90	65–80
Industrial Suitability	Limited	Moderate	Good	Excellent
Compatibility with Sintering	Poor	Moderate	Good	Very Good

Table 4: Common Biomass Materials Used for Torrefaction

Biomass Type	Moisture Content (%)	Calorific Value Before Torrefaction (MJ/kg)	Calorific Value After Torrefaction (MJ/kg)	Major Advantage
Rice Husk	8–15	12–15	18–22	Abundant agricultural waste
Sawdust	10–20	14–18	20–24	Good grindability
Bagasse	40–50	10–14	18–22	Easily available in sugar industry
Bamboo Residue	8–12	16–18	22–26	Fast ignition behavior
Coconut Shell	5–10	18–20	24–28	High fixed carbon
Palm Kernel Shell	6–12	17–19	23–27	Excellent combustion stability
Wood Chips	10–25	14–18	20–25	Uniform thermal

				behavior
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Table 5: Advantages of Torrefied Biomass in Iron Ore Sintering

Property Improved	Effect on Sintering Process
Reduced Moisture Content	Lower heat loss during combustion
Higher Calorific Value	Improved heat generation
Better Grindability	Easier particle size control
Improved Hydrophobicity	Better storage stability
Increased Carbon Content	Enhanced combustion efficiency
Controlled Volatile Matter	Stable thermal profile
Higher Bulk Density	Improved feeding and transportation
Reduced Biological Degradation	Longer storage life
Coal-like Characteristics	Better compatibility with coke breeze
Lower Smoke Generation	Cleaner industrial operation

4. Result and Discussion

The properties of biomass applied to produce iron ore sintering have been considerably improved through the process of torrefaction. Based on experimental results, it can be observed that the presence of high moisture content, low bulk density, high amount of volatile matter, and the unstable burning of raw biomass have prevented its application as an alternative material to coke breeze. There is an improvement in fuel quality, combustion efficiency, grindability, and storability as a result of torrefaction, along with the coal-like properties acquired from torrefaction.

The reduction of moisture content was among the noticeable changes due to torrefaction. It should be taken into account that high moisture content of raw biomass reduces combustion efficiency since additional heat energy is required to remove the moisture content during the sintering process. Thermal efficiency and consistent combustion were among the consequences of the effective elimination of free and chemically-bound moisture content from the biomass matrix by the process of torrefaction. The decrease in moisture content in biomass facilitated easy storage and minimized microbial degradation. Torrefaction led to a substantial increase in the calorific value of biomass due to the loss of oxygen-containing volatile organic matter and higher carbon content. The torrefied biomass released greater thermal energy upon combustion than non-treated biomass. An increased calorific value enabled the release of greater heat within the sintering zone and reduced the dependency on conventional coke breeze. Higher energy density facilitated the efficient transportation of biomass. Also, the brittleness and grindability of biomass feedstock increased due to torrefaction. Generally, the biomass material was characterized by elasticity and fiber content, making it difficult to grind. After being subjected to torrefaction, the biomass material exhibited brittleness, thus facilitating its grinding to uniform particle size. Uniformity in particle size led to stability in airflow distribution in the sinter bed, hence increasing the mixing of the fuel with iron ore fines. Also, better grindability promoted better interaction with existing fuel handling infrastructure and reduced energy input during fuel preparation. It was found out that the torrefied biomass had better control and stability when burning compared to raw biomass. This was attributed to its high volatile matter content and poor temperature distribution during sintering. As a result of the presence of more fixed carbon and less volatile matter, the burning rate became slower and uniform. Quality improvement of the produced sinter as well as heat conditions in the sintering bed was facilitated by the process of controlled combustion. In addition, the chances of occurrence of uncontrolled combustion and thermal deviations under industrial conditions were minimized due to steady heat production. After briquetting and torrefaction treatments, the bulk density of the biomass increased. Increased bulk density resulted in easy fuel supply during the sintering process, reduction in space for storage, and efficient transportation. Comparing to loose biomass particles, briquetted torrefied biomass demonstrated lower dust formation and better mechanical properties. Handling properties of the material under industrial conditions also became better. Torrefied biomass proved superior to the conventional coke breeze in respect to environmental performance. Since biomass has lower sulfur and nitrogen content, it generated less amounts of sulfur oxide and nitrogen oxide during combustion. Thus, torrefied biomass

was employed as a substitute for coke breeze, thereby minimizing carbon dioxide emissions and favoring the development of an eco-friendly process of steel-making. The use of waste products generated by forestry and agriculture as biomass also facilitated recycling of trash.

Furthermore, according to the experiments conducted, sintering properties were satisfactory for low to moderate levels of biomass substitution without having a detrimental effect on the amount of sinter formed. Within the limits of maintaining adequate combustion and thermal properties, low to moderate levels of substitution improved environmental properties. Nevertheless, owing to insufficient heating and fast combustion, extremely high biomass substitution sometimes adversely affected sinter strength. Optimization of biomass ratio and torrefaction process parameters is required for successful implementation of biomass in industrial applications. Results revealed that the quality and properties of biomass and their combustion behavior were greatly influenced by torrefaction temperature. High temperatures resulted in low mass yields of biomass owing to devolatilization, whereas low torrefaction temperatures yielded slightly better results in terms of fuel quality. The optimal energy density, stability of combustion, and solid mass were obtained through moderate torrefaction process. Particle size and residence time were found to influence quality of torrefied product.

Torrefaction can be used as a viable option for improving the quality of biomass for use in iron ore sintering industry. The method proved successful in enhancing the energy content, grindability, hydrophobicity, combustion stability, and storage characteristics of the biomass fuels. The torrefaction process of biomass exhibited great potential as an alternative fuel source to replace the use of iron ore in sintering operations.

5. Conclusion

It has been established through the present study that biomass is very promising as an alternative fuel that is eco-friendly and renewable for iron ore sintering. Nonetheless, various unfavorable attributes, such as excessive moisture, low density, high volatiles, low grindability, and unpredictable burning, prevent the utilization of the biomass feedstock as-is in its natural state. In industrial sintering operations, these limitations reduce thermal efficiency and pose operational difficulties. Torrefaction emerged as an effective method of upgrading biomass, which enhanced numerous physical, chemical, and thermal properties of the biomass fuel. The process elevated carbon content, energy value, hydrophobicity, and burning efficiency while reducing moisture and volatiles. Torrefied biomass is more suitable for combustion along with conventional fuels due to better grindability and coal-like nature of biomass in iron ore sintering plants. Moreover, the study revealed that briquetting improved the suitability of biomass due to higher bulk density, mechanical strength, storage ability, and transportation properties. As compared with loose raw biomass, biomass briquettes have proved more stable and effective in terms of combustion efficiency, low dust formation, and improved handling properties. Stable combustion leads to better heat generation in the sintering bed, resulting in stable sinter formation. From experimental results, it was found that utilization of torrefied biomass as a partial substitute for coke breeze reduces GHG emissions, fossil fuel consumption, and no significant decrease was observed in the production of sinter. Due to their low sulfur and nitrogen content, biomass-based fuels emitted lower levels of sulfur oxide and nitrogen oxide, thus promoting environmentally friendly steel production techniques. Despite the advantages associated with torrefaction and briquetting, there are several constraints such as preprocessing cost, energy input, biomass availability, and process optimization that hinder their full industrial implementation. For industrial-level processes, there is a need for further research on optimal conditions for torrefaction, biomass replacement rates, reactor design, and cost-effectiveness. Having analyzed all aspects, torrefied and briquetted biomass can be considered an appropriate fuel source for iron ore sintering and has a great potential to reduce carbon footprint, improve waste management, and foster sustainable development in the iron and steel industry.

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