

Review

Review on the Application and Development of Biochar in Ironmaking Production

Shijie Wang ¹, Yifan Chai ^{1,*}, Yici Wang ¹, Guoping Luo ¹ and Shengli An ^{1,2} 

¹ School of Materials and Metallurgy, Inner Mongolia University of Science and Technology, Baotou 014000, China; wang346223@163.com (S.W.); wangyici01060@163.com (Y.W.); luoguping3@126.com (G.L.); san@imust.edu.cn (S.A.)

² Inner Mongolia Key Laboratory of Advanced Ceramic Materials and Devices, Baotou 014000, China

* Correspondence: chaiyifan@live.cn

Abstract: In recent years, the concept of green, low-carbon and clean energy consumption has been deeply rooted in the hearts of the people, and countries have actively advocated the use of new energy. In the face of problems such as resource shortage and environmental pollution, we began to explore the use of new fuels instead of coal for production. Biomass resources have the characteristics of being renewable and carbon neutral and having large output. As an energy utilization, it is helpful to promote the transformation of the energy structure in various countries. Applying it to ironmaking production is not only conducive to energy conservation and emission reduction in the ironmaking process but also can achieve efficient utilization of crop waste. By introducing the source and main preparation methods of biochar, this paper expounds the main links and advantages of biochar in the ironmaking process and puts forward the direction of biochar in ironmaking in the future.

Keywords: biochar; ironmaking; low-carbon metallurgy; energy saving and emission reduction; utilization of resource comprehensive



Citation: Wang, S.; Chai, Y.; Wang, Y.; Luo, G.; An, S. Review on the Application and Development of Biochar in Ironmaking Production. *Metals* **2023**, *13*, 1844. <https://doi.org/10.3390/met13111844>

Academic Editor: Hong Yong Sohn

Received: 7 October 2023

Revised: 27 October 2023

Accepted: 1 November 2023

Published: 3 November 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Climate change is a major global challenge facing human society today. The emission of carbon dioxide and other polluting gases has a huge impact on the world environment [1]. The iron and steel industry is an important basic industry to promote the development of the national economy, an important support for building a modern power, and also a large energy consumer and contributor to CO₂ emissions. According to statistics, in 2021, China's annual energy consumption reached 5.24 billion tons of standard coal, of which coal resource consumption accounts for 56.0% of total energy consumption [2,3]. The ironmaking process is the highest part of CO₂ emissions in the steel production sector, which is due to the extensive use of fossil fuels to heat, melt, and reduce iron ore [4]. At present, China's steel production is still dominated by a long process, high carbon emission intensity, large energy consumption, and serious environmental pollution. According to the EU's goal, fossil carbon dioxide emissions should be reduced by 80% by 2050 [5]. Japan's COURSE50 project reduces CO₂ emissions by 10% with hydrogen reduction and separates and recovers CO₂ from blast furnace gas to reduce carbon by 20% [6]. The COOLSTAR project in South Korea reduces CO₂ emissions by 15% via modifying the by-product gas of the steel plant to prepare 'gray hydrogen' and injecting it into the blast furnace as a reducing agent [7]. ThyssenKrupp Group in Germany has made a breakthrough in the 'hydrogen instead of coal' blast furnace, achieving a 16% reduction in CO₂ emissions [8]. Brazil has partially replaced pulverized coal with charcoal powder for blast furnace injection, achieving a carbon reduction of 30% [9]. The Swedish iron and steel industry (ISI) sector, which is heavily dependent on fossil fuels and reducing agents, together with the mining industry, accounts for 63% of Sweden's industrial fossil energy use and 46% of greenhouse gas emissions, so it plans to reduce its fossil carbon dioxide emissions in the short to

medium term [10]. The European Union (EU) has set climate targets to gradually reduce greenhouse gas emissions by 80% via increasing the share of renewable energy in the energy structure and improving energy efficiency [11]. Therefore, the steel industry is considered to be an energy-intensive industry in all countries, especially since energy conservation and climate change issues (including polluting gas emissions, dust generation, etc.) have driven energy and ecological transformation [12]. The CO₂ footprint of a direct reduction plant fed with biomass-based reducing gas is more than 80% lower compared with the conventional blast furnace route. The biomass-based production of reducing gas could definitely make a reasonable contribution to a reduction in fossil CO₂ emissions within the iron and steel sector in Austria [13]. It is particularly important for countries to seek a green and low-carbon production method, use clean fuel for production, and fundamentally solve a series of problems brought on by production. As the iron ore reduction process in the blast furnace is fully dependent on carbon, mainly supplied by coal and coke, bioenergy is the only renewable energy that presents a possibility for their partial substitution [11]. As a renewable energy, biomass is a globally recognized clean and low-carbon fuel, which has great advantages compared with traditional fossil energy. The content of N and S in biomass is low, which can reduce the emission of SO₂ and other pollutants in production. Because of its carbon neutral characteristics, it can partially realize the carbon neutral cycle of the ironmaking process in iron and steel production, thereby reducing CO₂ emissions and reducing environmental pollution by the greatest extent. The use of renewable biomass in the industry is likely to reduce greenhouse gas emissions by 10% in 2050, which is equivalent to a 25% reduction in expected emissions from the industrial sector, equivalent to the current total carbon dioxide emissions in Germany, France, Italy, and Spain [14]. With the proposal of the ‘double carbon’ target [15,16], the steel industry is facing the transformation and upgrading of energy saving and carbon reduction, and the application of biomass energy in steel production has also received extensive attention. From the perspective of the ironmaking process application technology, biomass generally has the disadvantages of high moisture and alkali metal content, low fixed carbon content and calorific value, and low energy density. The development of biomass treatment technology can be efficiently applied to the ironmaking production process, which is the key to promote the industrial application of biomass metallurgy.

2. Development Status of Low Carbon Ironmaking Technology

With the gradual implementation of the ‘double carbon’ goal, the ironmaking process is facing an arduous task of carbon emission reduction, and there is an urgent need to develop low-carbon ironmaking technology that can significantly reduce carbon emissions. In recent years, China’s pig iron production has shown an overall upward trend. At present, China’s pig iron production has accounted for about 60% of the world’s total. The path of blast furnace ironmaking technology to achieve green and low carbon should adhere to the development path of optimizing agglomeration technology, improving blast furnace operation, pursuing blast furnace longevity, and comprehensive utilization of resources and non-blast furnace technology [17]. At present, many iron and steel enterprises and research units at home and abroad have begun to explore cutting-edge technologies such as low-carbon metallurgy and hydrogen metallurgy. Some enterprises in China, such as Baowu, Hegang, and An gang, have successively carried out low-carbon smelting or hydrogen metallurgy test work. Xuangang and Zhangang have studied the direct reduction technology of a syngas-based furnace. Shou gang and Tang gang have optimized the process flow under the conditions of reasonable production scale, combined with resources, energy supply, and process technology and equipment, and achieved high-efficiency and low-carbon coordinated development by continuously improving and optimizing the structure of furnace burden, optimizing the operation of the blast furnace, and strengthening the operation of the blast furnace [18]. In terms of the sintering process, JFE Iron and Steel Company of Japan proposed a material surface injection process to reduce the consumption of solid fuel by injecting natural gas [19]. China Shougang also achieved solid fuel reduction

by injecting steam into the sintering surface [20]. In terms of the pelletizing process, the proportion of pellets into the blast furnace in European countries is generally 80% to 90%. Some Chinese enterprises are also increasing the proportion of pellets into the furnace, thus reducing the carbon emissions of the iron and steel industry. For non-blast furnace ironmaking, China Bao wu Xinjiang Bayi Steel tested the hydrogen-rich carbon cycle of the blast furnace. Arcelor Mittal Steel Corporation (Luxembourg, Europe) commissioned Midrex to design a full-hydrogen direct reduction ironmaking plant with an annual output of 100,000 tons of DRI in Hamburg, Germany. Europe's ULCOS, Sweden's HYBRIT, and Germany's SALCOS projects are based on hydrogen direct reduction of iron as the main development process [18]. Environmental problems are faced by any country in the world. Some countries have applied biomass to ironmaking technology. Japan has developed and utilized new technologies for producing coke from low-grade carbonaceous resources (biomass, lignite and non-caking coal) to reduce CO₂ emissions during ironmaking [21]. Brazil's ArcelorMittal is developing biomass carbon smelting technology that uses artificially planted eucalyptus forests as fuel for small blast furnaces [22]. Australian Steel has studied two CO₂ projects: using biomass as a blast furnace fuel to achieve carbon balance and zero CO₂ emissions [23]. The Canadian iron and steel industry envisages replacing fossil carbon with biomass carbon (3–5 years) to achieve a significant reduction in greenhouse gases. The CCRA (Canadian Carbonization Research Association) and the Ganmet ENERY'S Metallurgical Fuel Laboratory (MFL) have identified conditions for reducing greenhouse gases in blast furnace ironmaking by replacing the coal used in pulverized coal injection (PCI) with solid biomass carbon [24]. Under the situation of 'double carbon' development, in the process of green and low-carbon development, the ironmaking system must pay attention to the rationalization of the process structure and the green and low-carbon coordinated development of all walks of life. On the basis of existing technology, continuous innovation is still needed. Upgrading and reforming green manufacturing is the only way for development. It is necessary to speed up the development and utilization of green clean energy as a production material. Therefore, biomass energy has become the focus of attention of all countries.

3. Summary of Biomass Resources

There are many kinds of biomass resources and huge reserves in China, as shown in Table 1 below. According to relevant statistics [25], China's agricultural and forestry waste resources are currently 1.5 billion tons, equivalent to 740 million tons of standard coal, of which about 460 million tons of standard coal can be used. By the end of 2015, there were 900 million tons of waste straw resources in China, of which 500 million tons were reasonably developed and utilized. The total annual output of firewood was 200 million tons, equivalent to 116 million tons of standard coal. The livestock breeding industry produces about 2 billion tons of feces, converted into biogas for 1950 billion m³, equivalent to 310 million tons of standard coal; according to the actual data, China's straw can be harvested at a total of about 450 million tons per year, equivalent to 180 million tons of standard coal. However, compared with the annual average consumption of fossil energy in China's primary energy, the share of biomass resources is not high, and its development and application prospects are very broad.

Table 1. Main biomass energy resources in China [26].

Type	Physical Resources $\times 10^8$ t	Total Energy Potential $\times 10^{19}$ J	Theory Can Obtain Energy $\times 10^{19}$ J
Straw	7.28	1.05	0.52
Animal manure	39.26	5.51	0.30
Forestry biomass	21.75	3.64	0.49
Municipal waste	1.55	0.06	0.03
Municipal wastewater	482.40	0.03	0.01
Amounta to	552.24	10.29	1.35

Biomass can be converted into gas, liquid, and solid fuels, making it a clean and renewable carbon resource [27]. Since 2014, China has ranked first in the world in terms of renewable energy consumption. China plans to increase the proportion of renewable energy applications to 20% by 2030. At the same time, governments at all levels have also introduced relevant policies to encourage the development of biomass energy. At the same time, they have pointed out the direction for the development of biomass energy and will vigorously promote the development of bioliquid fuels, biomass power generation, biomass heating, bio-natural gas, and other technologies [28].

4. Preparation of Biochar

The use of biomass carbon must meet the requirements of iron and steel production. For example, biomass as a fuel for blast furnace injection must meet the physical, chemical, and technological properties of the fuel in the furnace. From a physical point of view, biomass must be crushed and screened to a suitable particle size for injection. From a chemical point of view, biomass must have similar chemical composition and combustion reactivity to coal for injection. The composition and structure of raw biomass are very different from those of pulverized coal. Compared with pulverized coal, the calorific value, fixed carbon content, grindability, and energy density of biomass are lower, the volume is larger, and the moisture and volatile content are higher. These differences greatly affect the direct and effective utilization of biomass in the steel production process. Over the past decade, antipyretics have developed into a promising thermochemical technology that can modify microorganisms under inert gas or anoxic conditions. Like the original microorganisms, the solid material obtained by biomass pyrolysis is called biomass semi-coke, which has a lower moisture concentration, greater carbon concentration, and greater calorific value and energy density. Under certain pyrolysis conditions, it can achieve the need for high-temperature jet fuel.

Pyrolysis is a thermal decomposition process that occurs in the absence of oxygen. Pyrolysis converts biomass rich in lignocellulose into gases, liquids, and solids rich in carbon. The main components of lignocellulosic biomass are cellulose, hemicellulose, and lignin, which are high molecular polymers. In the temperature range of 300~500 °C, these polymers are converted into combustible gases, bio-oil, and biochar to varying degrees through decomposition and polycondensation. Pyrolysis technology can be divided into slow, fast, and flash pyrolysis [29]; the most commonly used are slow and fast pyrolysis processes. Different heating rates have an important influence on the composition of pyrolysis products. Table 2 shows the analysis of different types of pyrolysis parameters.

Table 2. Analysis of different types of pyrolysis parameters.

Pyrolysis Type	low Speed	Fast	Flash
Residence time (s)	500~6500	0.4~6	<1
Particle size (mm)	5~50	<1	<0.030
Heating rate (°C/s)	0.05~1	5~200	1000
Reaction temperature (°C)	300~700	600~1150	400~900
Production	G, L, S	L	L

(Note: G, L, and S represent combustible gas, biomass fuel, and biomass char, respectively).

5. Application of Biochar in the Ironmaking Process

In recent years, biochar has been widely used in the ironmaking process [30]. In addition to the mixed injection of the blast furnace, researchers have also tried to add biochar to sintering, coking, iron ore reduction, and other processes (as shown in Figure 1) to replace some pulverized coal to reduce fossil energy consumption.

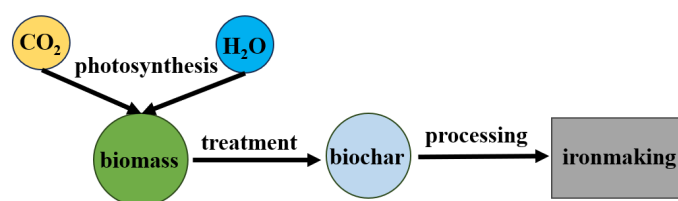


Figure 1. Partial application of biochar in blast furnace ironmaking process.

5.1. Application of Biochar in Coking Process

Coke is an indispensable material in the blast furnace, providing a permeable matrix for slag and metal to pass through during the falling process and hot gas to penetrate during the rising process, while generating the required gas to reduce iron oxide (CO). Coke reactivity is a very important parameter to determine the quality of coke. Applying biomass to the coking process helps to reduce the temperature of the reserve area of the blast furnace and reduce the energy required for production. Seo, M et al. [31] used boxwood as a raw material to add to coking coal in different proportions (0, 10, 15, 20, and 30 wt%) and carbonized it at different final temperatures (500–800 °C) to generate biochar. The calorific value of biochar is between 7200–7560 Kcal/kg, which is higher than the standard value (7000 Kcal/kg), indicating that biochar can be a suitable substitute for traditional fossil fuels and has the potential to reduce carbon dioxide emissions in the ironmaking industry. Yuuki, M et al. [32] used woody biomass to produce coke and used vapor deposition (VD) and other methods to explore the properties of coke and the study of composite/coal mixtures for gasification reactions; they determined that the optimal coal blending amount depends on the type of caking coal. It was found that 3–15 wt% of biomass can be used as coke addition for coke production. KHASRAW et al. [33] studied the gasification behavior of coke generated by different carbon sources and rapid devolatilization in the process of HIsarna substitution for ironmaking. It was concluded that the gasification reaction of charcoal before and after rapid heat treatment was the fastest, and the reaction of Bana peat raw material was more intense than that of hot coal raw material. At 1500 °C, the gasification behavior of Bana peat is very similar to that of hot coal. Among them, Bana peat is most seriously affected by rapid devolatilization. The reason is that it has high ash content, and the high ash content melts during heat treatment, resulting in pore blockage. MacPhee J A et al. [34] studied the effects of blend composition, heating rate, and particle size of charcoal on the quality of coke by producing industrial-grade coke in coking coal mixture with up to 10% charcoal. The results show that the introduction of finely crushed charcoal into the coking coal mixture will produce low-quality coke, the large-size charcoal is beneficial to the formation of high-quality coke, and the addition of charcoal can effectively reduce CO₂ emissions. Gan, M et al. [35] has reported that the properties of biochar and traditional coke powder are significantly different. Both scanning electron microscopy (SEM) and specific surface analysis (BET) results show that biochar has a large number of micropores and is evenly distributed. The specific surface area for three biochars decreases in the following order: straw char > wood char > fruit pit char [36,37]. Wang, G.W et al. [38] explored the morphology and reactivity of biomass char prepared under different atmospheres at high temperatures so that biomass can be better applied to the coking process. Lu, Y. C et al. [39] explored the potential of hydrogen coke (a solid product from hydrothermal pyrolysis of organic feedstock) and charcoal as replacements for coke and coal consumption in steel and steelmaking processes to reduce greenhouse gas emissions and proved the feasibility of hydrothermal carbon and charcoal as carburizers through experiments. Kieush, L et al. [40] used a sinter reduction test to study the effect of coke and biocoke on the physical and chemical properties of sinter and proved that adding 15 wt% biomass particles at 950 °C can replace industrial coke powder.

5.2. Application of Biochar in Sintering Operation

Traditional iron ore sintering is dominated by coke powder, and the CO₂ emissions generated during the sintering process account for 11% of the steel process [30], second only to the blast furnace. The application of biomass to iron ore sintering reduces the use of coke powder from the source and reduces the emission of polluting gases, as shown in Figure 2. To this end, scholars at home and abroad have conducted a series of studies.

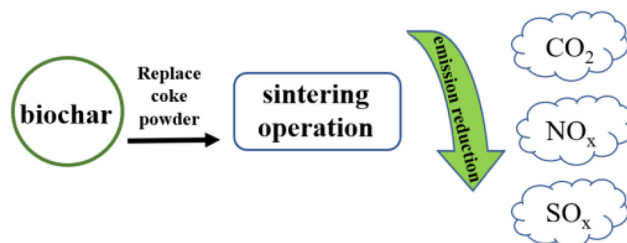


Figure 2. Application of biochar in sintering process.

Gan, M et al. [41] used fruit core biochar instead of coke powder to conduct sintering experiments at different ratios to study the effect of adding fruit core charcoal on sintering. The results showed that the appropriate ratio of fruit stone charcoal to replace coke powder was 40%, which had little impact on the production and quality of sintered ore. However, the emissions of CO₂, NO_x, and SO_x were reduced by 23.05%, 30.99%, and 42.77%, respectively, achieving a good emission reduction effect. Liu, C et al. [42] used modified charcoal instead of coke for iron ore sintering. By modifying the specific surface area of biomass fuel with CaO and urea, the optimal proportion of modified charcoal instead of coke powder was determined through sintering experiments. 40% modified charcoal was used for sintering to reduce 45.85% of SO₂ and 54.26% of NO_x, with the aim of achieving pollutant reduction. Jha G et al. [43] successfully used 10% sawdust, 30% charcoal, and a combination of 30% sawdust and charcoal to replace coke under the condition of meeting the standard of sinter reducibility and strength performance, and finally determined the feasibility of biomass for iron ore sintering by comparing the temperature rise of charcoal and coke within a certain period of time. Frohlichova et al. [44] and Lu et al. [45] found through approximate and final analysis, as well as GCV (Gross Calorific Value) characterization, that biomass with a size of 1 mm is the most preferred for sintering processes. Ooi et al. [46] conducted sintering experiments using charcoal as fuel and found that 20% of charcoal and coke powder can provide the same energy. Jha G et al. [43] studied the applicability of biomass in iron ore sintering processes, systematically analyzed the characteristics of biomass, and conducted sintering experiments using biomass coke and charcoal coke combinations to effectively replace some coal resources.

5.3. Application of Biochar in Iron Ore Reduction

Biomass carbon is low-carbon and environmentally friendly. The use of biomass for iron ore reduction can achieve the green development of iron and steel enterprises, and the application of some biomass carbon can also effectively improve the reduction capacity of iron ore. Biomass carbon can not only reduce iron oxides by its own carbon but also pyrolysis. The reduction gas reacts with iron oxides to improve the reduction efficiency, and the gas–solid synergistic effect of biomass carbon is used to reduce iron ore, as shown in Figure 3. The use of biochar to reduce iron ore not only improves the reduction efficiency but also contributes to the protection of the environment.

Huang, Z.C et al. [47] carried out experiments on the temperature reduction of iron concentrate by pine wood. The results showed that biomass could be pyrolyzed to generate CO, CO₂, CH₄, C₂H₄, H₂, and other gases. Due to the increase in pyrolysis temperature, the proportion of CO and H₂ in the reduced iron oxide was significantly increased. When the molar ratio of carbon to iron was 0.4 and the reduction temperature was 1050 °C, the metallization rate of the reduced material was 82.97%, which could efficiently reduce the

iron concentrate at low temperatures. Han, H et al. [48] used biomass (bamboo charcoal, charcoal, and straw fiber) to provide a theoretical and technical basis for the direct reduction of iron by the rotary hearth furnace process and explored the combination of biomass instead of coal to produce higher metallized pellets. Fan, X et al. [49] studied the application of different proportions of charcoal instead of coke powder in sample production. When charcoal was used to replace 40% coke, the porosity and FeO content of the sample also increased, resulting in the reduction rate index increasing from 79.8% to 84.3% so that the reduction performance was effectively improved. Nayak D et al. [50] applied waste coconut shell to the reduction roasting experiment of goethite covering layer. Through experiments, it was found that under the optimal conditions, namely, 800 °C temperature, 60 min time, and 0.2 biomass feed ratio, the cover sample with 49% Fe can be upgraded to a concentrate with 63.2% Fe, and the iron recovery rate is 66.2%. Using coconut shells as a reducing agent, the process can solve environmental problems by replacing the use of coal and reducing the burden of dumping agricultural waste and iron ore cover. Zhang, J.L et al. [51] used biochar to rapidly reduce iron ore. It was found that the reduction temperature was 106 °C lower than that of pulverized coal and 208 °C lower than that of coke powder. The maximum reaction rate was 1.57 times that of pulverized coal reduction. The final reaction fraction was 17~20% higher than that of pulverized coal and coke powder. Guo, D.B et al. [52–54] found that biomass particles and iron ore began to transform into metal Fe and aggregated into iron whiskers at 880 °C. At 900 °C, iron whiskers began to expand more. With the increase in reduction temperature, FeO gradually decreased and metal iron gradually increased.

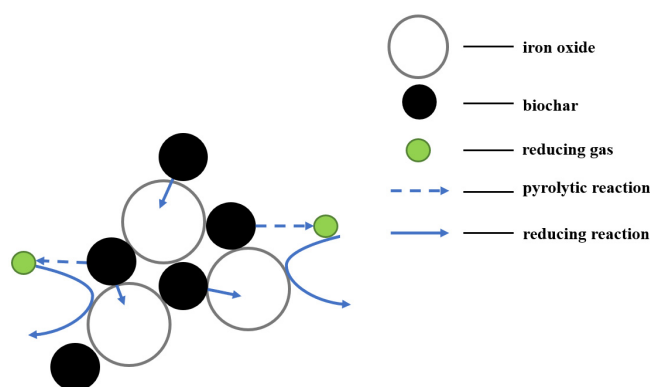


Figure 3. Application of biochar in reducing iron ore.

5.4. Biochar Used in Blast Furnace Injection

The co-combustion of biomass and pulverized coal is a very advantageous measure for using biomass to replace fossil fuels. Moreover, biomass has good flammability, and co-combustion with pulverized coal can promote the combustion reaction of pulverized coal. Therefore, many scholars at home and abroad have carried out a lot of research on the co-combustion characteristics and co-combustion products of biomass and pulverized coal and are committed to promoting the utilization of biomass resources. Chen W H et al. [55] studied the feasibility of injecting different types of biomass products such as charcoal, baking materials, and sawdust particles into blast furnaces to replace coal injection. The results show that charcoal has a significant effect on the operation of the blast furnace. Pulverized coal can be completely replaced by charcoal, while baking materials and sawdust particles can only be added in a small amount to blast furnace smelting. Through research, it is found that after the injection of charcoal, roasting materials, and sawdust particles, the annual CO₂ emission reduction potential of coal injection smelting is about 1140 kton, 260 kton, and 230 kton, respectively, which can effectively reduce CO₂ emissions. In addition, for the addition of biomass, the recycling of resources is also realized. Ng, Ka Wing et al. [56] used solid biofuels instead of pulverized coal injection (PCI) to significantly reduce greenhouse gas emissions from blast furnace ironmaking, systematically evaluated

the performance of biochar produced by different pyrolysis technologies, and established a technical and economic model to evaluate its use value (VIU). Wang, P et al. [57] carried out the basic research on the application of biomass-pyrolyzed semi-coke in blast furnace injection. The results show that the application of biomass semi-coke in blast furnace injection can reduce coke consumption and coal mining. And from its SEM, shown in Figure 4, it can be seen that both are irregular spherical particles. The surface of anthracite is smooth and dense, which is a solid material with invisible openings, while the palm shell is a developed porous structure, and the palm shell semi-coke blast furnace injection can develop indirect reduction, reduce the amount of coal injection, and ensure the stable operation of the blast furnace. Therefore, in theory, it is feasible to use palm shell semi-coke to replace a part of blast furnace pulverized coal injection.

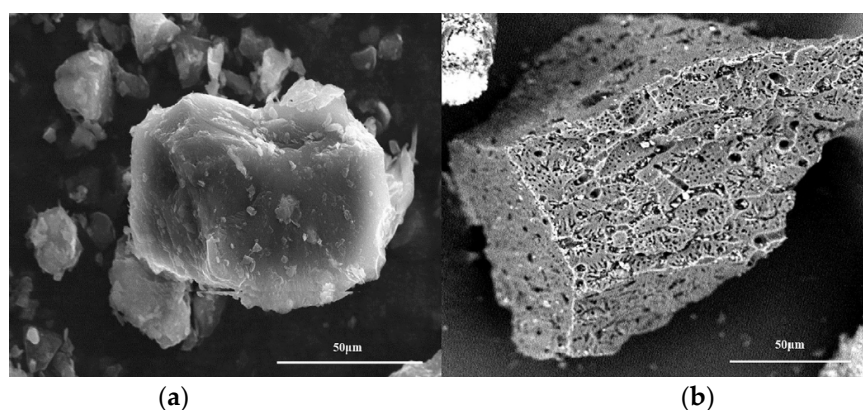


Figure 4. SEM images of (a) anthracite coal and (b) palm kernel shell char [58].

Li J et al. [58] systematically studied the physical and chemical properties of biomass residue char and anthracite by means of X-ray diffraction, scanning electron microscopy, and Raman spectroscopy. The combustion characteristics and mechanism of biomass residue, biomass residue char, anthracite and biomass residue char, and anthracite mixture were studied by thermogravimetric analysis. The addition of biomass residue biochar to anthracite can improve the combustion performance of anthracite. The combustion process of the mixed samples has an obvious synergistic effect. When the ratio of biomass residue to hydrochar is 60%, the activation energy of the mixed sample is 38.5 kJ/mol, which has good combustion characteristics in blast furnace smelting. Zheng, W.C et al. [59] showed that biomass had good combustion performance with different combustion temperatures of biomass and temperatures lower than the combustion temperature of coal. Xu, R.S [60], Jiang, Y.Y [61] and Wijavanta [62] studied the basic properties of biomass such as grindability and proved the feasibility of applying biomass to blast furnace injection. Wang, C et al. [63] developed a static heat and mass balance model and investigated the replacement rate of charcoal, pyrolysis materials, and wood pellets for blast furnace coal injection; they reported that 166.7 kg/t of charcoal could replace 155 kg/t of pulverized coal. Pyrolysis material and wood pellets could replace 22.8% and 20% of pulverized coal, respectively. By increasing the charcoal injection rate between 200 and 220 kg/t, the net CO₂ emissions may be decreased by 40%. Mathieson et al. [64] estimated that using biomass in blast furnace injection would reduce CO₂ emissions by 0.4–0.6 t per ton of steel. Wang Guangwei et al. [65] used the hydrothermal carbonization process (HTC) to prepare corn straw hydrothermal carbon as solid fuel for blast furnace injection and studied the microstructure of hydrogen coke prepared under different conditions via SEM technology. It can be seen from Figure 5 that the microstructure of the sample changes with the increase in heat treatment temperature and the sample becomes a smooth, flat, and highly organized fiber structure with dense pores. Through characterization analysis, it is verified that the combustion reactivity of the HTC process is better than that of bituminous coal, which can be used as an effective method to convert corn stalk biomass into blast furnace injection fuel.

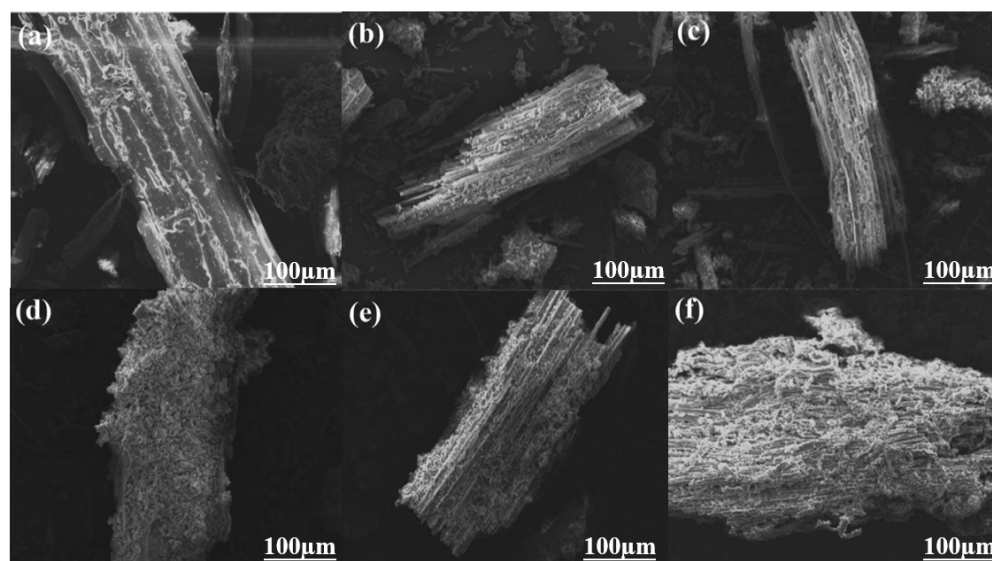


Figure 5. SEM images of (a) MS and hydrochar at HTC, (b) HTC-280-15, (c) HTC-280-30, (d) HTC-280-60, (e) HTC-280-90, and (f) HTC-280-120 [58].

Li Jinhua et al. [58] explored the mechanism of a mixed injection of biomass charcoal and anthracite and proved its feasibility.

6. Conclusions and Prospects

The iron and steel industry has the characteristics of high energy consumption and high pollution, which has always been the focus of energy conservation and emission reduction. Especially in the ironmaking production process, the energy consumption of the preparation process of ironmaking raw materials, such as sintering and pellets, usually accounts for more than 70% of the energy consumption of the whole process. The traditional energy structure is mainly based on coal. At present, the use of biomass resources in ironmaking production, coking, sintering, pelletizing, blast furnace smelting, and other processes is not only conducive to energy conservation and emission reduction in the ironmaking process but also can effectively reduce the consumption of fossil energy and reduce CO₂ emissions. Biomass replaces some traditional fossil fuels; it is concluded from the research that the performance of some biomass is better than that of traditional raw materials, and it can play a better role in each ironmaking process. It can be seen that biomass carbon has great development prospects instead of non-renewable resources such as coal. At this stage, only part of the biochar is used instead of pulverized coal in production. In the future, more research can be carried out to make biochar fully replace more of the pulverized coal in production. Therefore, we can reduce the emission of pollutants by a greater extent, take measures to protect the environment by a greater extent, better adapt to the development and progress of the times, and better realize the important strategy of improving environmental pollution. We should look to fully apply biomass technology to the ironmaking industry to make biomass technology play a better role in the field of ironmaking. In the future, biomass will be better used instead of fossil fuels, instead of pulverized coal injection blast furnaces, instead of the pulverized coal reduction of iron ore, and other aspects, giving full play to its clean and renewable role. In the process of production and development in the future, countries should speed up the research and development of the green new technology industry but also fulfill the ‘double carbon’ principle, ensuring production and development achieve a win-win situation.

Author Contributions: Conceptualization, S.W., Y.C. and Y.W.; validation, G.L.; writing—original draft preparation S.W.; writing—review and editing Y.C. and S.A.; funding acquisition, Y.C. and S.A. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (No. 52364043), the Fundamental Research Funds for Inner Mongolia University of Science Technology (No. 2022043), the Program for Young Talents of Science and Technology in Universities of the Inner Mongolia Autonomous Region (No. NJYT22060).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Wang, G.; Zhang, H.Q. Carbon emission status and carbon reduction prospect of iron and steel industry in China. *Chem. Miner. Process.* **2021**, *50*, 55–64.
- In 2021 China's raw coal production will reach 4.13 billion tons. *China Coal News*, 1 March 2022.
- He, K.; Wang, L. Development and current situation of energy consumption in iron and steel industry in China. *China Metall.* **2021**, *31*, 26–35.
- Birat, J.P. Society, Materials, and the Environment: The Case of Steel. *Metals* **2020**, *10*, 331. [\[CrossRef\]](#)
- Mousa, E.; Wang, C.; Riesbeck, J.; Larsson, M. Biomass applications in iron and steel industry: An overview of challenges and opportunities. *Renew. Sustain. Energy Rev.* **2016**, *65*, 1247–1266. [\[CrossRef\]](#)
- Liu, W.Q. Research on low carbon ironmaking technology. *China Environ. Prot. Ind.* **2011**, *01*, 20–25.
- Wang, D.W. Development status and future prospects of 'hydrogen metallurgy'. *Metall. Manag.* **2021**, *14*, 47–49.
- Wei, R.F.; Zhu, Y.L.; Long, H.M.; Xu, C.B. Research status and prospect of biomass iron ore pellets. *Sintered Pellet.* **2022**, *47*, 29–37.
- Machado, J.G.M.S.; Oso'rio, E.; Vilela, A.C.F.; Babich, A.; Senk, D.; Gudenau, H.W. Reactivity and conversion behaviour of Brazilian and imported coals, charcoal and blends in view of their injection into blast furnaces. *Steel Res. Int.* **2010**, *81*, 9–16. [\[CrossRef\]](#)
- Nwachukwu, C.M.; Olofsson, E.; Lundmark, R.; Wetterlund, E. Evaluating fuel switching options in the Swedish iron and steel industry under increased competition for forest biomass. *Appl. Energy* **2022**, *324*, 119878. [\[CrossRef\]](#)
- Mandova, H.; Leduc, S.; Wang, C.; Wetterlund, E.; Patrizio, P.; Gale, W.; Kraxner, F. Possibilities for CO₂ emission reduction using biomass in European integrated steel plants. *Biomass Bioenergy* **2018**, *115*, 231–243. [\[CrossRef\]](#)
- Ladanai, S.; Vinterbäck, J. *Global Potential of Sustainable Biomass for Energy*; Department of Energy and Technology, Swedish University of Agriculture Sciences: Uppsala, Sweden, 2009; pp. 1654–9406.
- Hammerschmid, M.; Müller, S.; Fuchs, J.; Hofbauer, H. Evaluation of biomass-based production of below zero emission reducing gas for the iron and steel industry. *Biomass Convers. Biorefinery* **2021**, *11*, 169–187. [\[CrossRef\]](#)
- Zhou, M.C.; Liu, W. Carbon emission reduction and biomass resource utilization. *Chem. Des.* **2022**, *32*, 11–14.
- Wang, X.D.; Shang, G.Q.; Xing, Y.; Hou, C.J.; Tian, J.L. Research on the low-carbon development technology route of iron and steel enterprises under the 'double carbon. *Chin. J. Eng.* **2023**, *45*, 853–862.
- Zhang, Q.; Zhang, W.; Wang, Y.L. Energy saving and emission reduction potential of China's iron and steel industry and ways to improve energy efficiency. *Steel* **2019**, *54*, 7–14.
- Zhang, J.L.; Liu, Z.J.; Li, K.J. 'Double carbon' strategy under the green low carbon development of ironmaking industry in China. *Ironmaking* **2022**, *41*, 1–10.
- Zhang, S.R.; Pan, G.Y.; Liu, M. The development path of ironmaking technology in China under the goal of 'double carbon'. *Ironmaking* **2022**, *41*, 1–7.
- Oyama, N.; Iwami, Y.; Yamamoto, T. Development of secondary-fuel injection technology for energy reduction in the iron ore sintering process. *ISIJ Int.* **2011**, *51*, 913–921. [\[CrossRef\]](#)
- Zhang, F.M. The development and prospect of green low-carbon ironmaking technology in ShouGang. *Steel* **2020**, *55*, 11–18.
- Suopajarvi, H.; Kempainen, A.; Haapakangas, J. Extensive review of the opportunities to use biomass-based fuels in iron and steel-making processes. *J. Clean. Prod.* **2017**, *148*, 709–734. [\[CrossRef\]](#)
- Pinto, R.G.D.; Szklo, A.S.; Rathmann, R. CO₂ emissions mitigation strategy in the Brazilian iron and steel sector—from structural to intensity effects. *Energy Policy* **2018**, *114*, 380–393. [\[CrossRef\]](#)
- Liu, Y.; Shen, Y. CFD study of charcoal combustion in a simulated iron-making blast furnace. *Fuel Process. Technol.* **2019**, *191*, 152–167. [\[CrossRef\]](#)
- Ng, K.W.; Giroux, L.; MacPhee, T.; Todoschuk, T. Direct injection of biofuel in blast furnace iron-making. In Proceedings of the AISTech—Iron and Steel Technology Conference Proceedings, Pittsburgh, PA, USA, 3–6 May 2010; pp. 643–652.
- Tian, Y.H.; Shan, M.; Kong, G.; Ma, L.W.; Shao, S. Research on the development strategy of biomass economy in China. *China Eng. Sci.* **2021**, *23*, 133–140.
- Du, S.W.; Chen, W.H.; Lucas, J.A. Pretreatment of biomass by torrefaction and carbonization for coal blend used in pulverized coal injection. *Bioresour. Technol.* **2014**, *161*, 333–339. [\[CrossRef\]](#) [\[PubMed\]](#)
- Yao, J.N. The potential of biomass energy utilization in China is about 460 million tons of standard coal. *China Energy News*, 20 September 2021; p. 019.
- Huo, L.L.; Zhao, L.X.; Yao, Z.L. Greenhouse gas emission reduction potential of agricultural biomass energy. *Acta Agric. Eng.* **2021**, *37*, 179–187.

29. Peng, W.M.; Wu, Q.Y. Biomass Pyrolysis Fuel Production. *New Energy* **2000**, *22*, 39–44.
30. Wei, R.F.; Zhang, L.L.; Cang, D.Q.; Li, J.X.; Li, X.W.; Xu, C.C. Current status and potential of biomass utilization in ferrous metallurgical industry. *Renew. Sustain. Energy Rev.* **2017**, *68*, 511–524. [\[CrossRef\]](#)
31. Seo, M.W.; Jeong, H.M.; Lee, W.J.; Yoon, S.J.; Ra, H.W.; Kim, Y.K.; Lee, D.; Han, S.W.; Kim, S.D. Carbonization characteristics of biomass/coking coal blends for the application of bio-coke. *Chem. Eng. J.* **2020**, *394*, 124943. [\[CrossRef\]](#)
32. Yuuki, M.; Naoto, T. Preparation of coke from biomass char modified by vapour deposition of tar generated during pyrolysis of woody biomass. *Ironmak. Steelmak.* **2022**, *49*, 646–657.
33. Khasraw, D.; Spooner, S.; Hage, H.; Meijer, K.; Li, Z. Devolatilisation characteristics of coal and biomass with respect to temperature and heating rate for HIsarna alternative ironmaking process. *Fuel* **2020**, *284*, 119101. [\[CrossRef\]](#)
34. MacPhee, J.A.; Gransden, J.F.; Giroux, L.; Price, J.T. Possible CO₂ mitigation via addition of charcoal to coking coal blends. *Fuel Process. Technol.* **2009**, *90*, 16–20. [\[CrossRef\]](#)
35. Gan, M.; Fan, X.; Ji, Z.; Chen, X.; Jiang, T.; Yu, Z. Effect of biomass fuel distribution in pellets on iron ore sintering and NO_x emission. *Iron Steelmak.* **2014**, *41*, 430–434. [\[CrossRef\]](#)
36. Gan, M.; Fan, X.; Ji, Z.; Jiang, T.; Chen, Z.Y.; Li, G.; Yin, L. The application of biomass fuel in iron ore sintering: Influence mechanism and emission reduction. *Iron Steelmak.* **2015**, *42*, 27–33. [\[CrossRef\]](#)
37. Gan, M.; Fan, X.H.; Chen, X.Y.; Ji, Z.Y.; Lv, W.; Wang, Y.; Yu, W.; Jiang, T. Reduction of pollutant emission in iron ore sintering process by applying biomass fuels. *ISIJ Int.* **2012**, *52*, 1574–1578. [\[CrossRef\]](#)
38. Wang, G.W. The structural characteristics and gasification reactivity of biochar pyrolyzed in different atmospheres at high temperature. *Energy* **2018**, *147*, 25–35. [\[CrossRef\]](#)
39. Lu, Y.C.; Brabie, L.; Karasev, A.V.; Wang, C. Applications of Hydrochar and Charcoal in the Iron and Steelmaking Industry—Part 2: Carburization of Liquid Iron by Addition of Iron–Carbon Briquettes. *Sustainability* **2022**, *14*, 5383. [\[CrossRef\]](#)
40. Kieush, L.; Koveria, A.; Boyko, M.; Yahnolnuyk, M.; Hrubia, A.; Molchanov, L.; Moklyak, V. Influence of biocoke on iron ore sintering performance and strength properties of sinter. *Min. Miner. Depos.* **2022**, *2*, 55–63. [\[CrossRef\]](#)
41. Gan, M.; Li, H.R.; Fan, X.H. Combustion characteristics of core biochar and its emission reduction behavior in sintering. *Sintered Pellets* **2022**, *47*, 65.
42. Liu, C.; Zhang, Y.Z.; Zhao, K.; Xing, H.W.; Kang, Y. Modified biomass fuel instead of coke for iron ore sintering. *Ironmak. Steelmak.* **2020**, *47*, 188–194. [\[CrossRef\]](#)
43. Jha, G.; Soren, S. Study on applicability of biomass in iron ore sintering process. *Renew. Sustain. Energy Rev.* **2017**, *80*, 399–407. [\[CrossRef\]](#)
44. Frohlichova, M.; Legemza, J.; Findorak, R. Biomass as a source of energy in iron ore agglomerate production process. *Arch. Metall. Mater.* **2014**, *59*, 815–820. [\[CrossRef\]](#)
45. Lu, L.M.; Adam, M.; Killburn, M.; Hapugoda, S.; Somerville, M.; Jahanshahi, S. Substitution of charcoal for coke breeze in iron ore sintering. *ISIJ Int.* **2013**, *53*, 1067–1616. [\[CrossRef\]](#)
46. Oci, T.C.; Aries, E.; Ewan, B.C.R.; Thompson, D.; Anderson, D.R.; Fisher, R.; Fray, T.; Tognarelli, D. The study of sunflower seed husks as a fuel in the iron ore sintering process. *Miner. Eng.* **2008**, *21*, 167–177.
47. Huang, Z.C.; Jin, Y.Y.; Yi, L.Y. Pyrolysis characteristics of biomass and its reduction of iron concentrate. *Sintered Pellets* **2021**, *46*, 65–71.
48. Han, H.; Duan, D.; Yuan, P.; Li, D. Biomass reducing agent utilisation in rotary hearth furnace process for DRI production. *Ironmak. Steelmak.* **2015**, *42*, 579–584. [\[CrossRef\]](#)
49. Fan, X.; Ji, Z.; Gan, M.; Chen, X.; Li, Q.; Liang, T. Influence of charcoal replacing coke on microstructure and reduction properties of iron ore sinter. *Ironmak. Steelmak.* **2016**, *43*, 5–10. [\[CrossRef\]](#)
50. Nayak, D.; Dash, N.; Ray, N.; Rath, S.S. Utilization of waste coconut shells in the reduction roasting of overburden from iron ore mines. *Powder Technol.* **2019**, *353*, 450–458. [\[CrossRef\]](#)
51. Zhang, J.L.; Guo, J.; Wang, G.W.; Xu, T.; Chai, Y.F.; Zheng, C.L.; Xu, R.S. Kinetics of petroleum coke/biomass blends during co-gasification. *Int. J. Miner. Metall. Mater.* **2016**, *23*, 1001–1010. [\[CrossRef\]](#)
52. Guo, D.; Zhu, L.; Guo, S.; Cui, B.; Luo, S.; Laghari, M.; Chen, Z.; Ma, C.; Zhou, Y.; Chen, J.; et al. Direct reduction of oxidized iron ore pellets using biomass syngas as the reducer. *Fuel Process. Technol.* **2016**, *148*, 276–281. [\[CrossRef\]](#)
53. Guo, D.B.; Li, B.Y.; Cui, B.H.; Chen, Z.H.; Luo, S.P. Direct reduction of iron ore/biomass composite pellets using simulated biomass-derived syngas: Experimental analysis and kinetic modelling. *Chem. Eng. J.* **2017**, *327*, 822–830. [\[CrossRef\]](#)
54. Guo, D.B.; Hu, M.; Pu, C.X.; Xiao, B.; Hu, Z.Q.; Liu, S.M. Kinetics and mechanisms of direct reduction of iron ore-biomass composite pellets with hydrogen gas. *Int. J. Hydrogen Energy* **2015**, *40*, 4733–4740. [\[CrossRef\]](#)
55. Chen, W.H.; Wu, J.S. An evaluation on rice husks and pulverized coal blends using a drop tube furnace and a thermogravimetric analyzer for application to a blast furnace. *Energy* **2009**, *34*, 1458–1466. [\[CrossRef\]](#)
56. Ng, W.K.; Giroux, L.; Todoschuk, T. Value-in-use of biocarbon fuel for direct injection in blast furnace ironmaking. *Ironmak. Steelmak.* **2018**, *45*, 1457837. [\[CrossRef\]](#)
57. Wang, P.; Wang, G.W.; Zhang, J.L.; Lee, J.Y.; Li, Y.J.; Wang, C. Co-combustion characteristics and kinetic study of anthracite coal and palm kernel shell char. *Appl. Therm. Eng.* **2018**, *143*, 736–745. [\[CrossRef\]](#)
58. Li, J.H.; Xu, R.S.; Wang, G.W.; Zhang, J.L.; Song, B.; Liang, W.; Wang, C. Study on the feasibility and co-combustion mechanism of mixed injection of biomass hydrochar and anthracite in blast furnace. *Fuel* **2021**, *304*, 121465. [\[CrossRef\]](#)

59. Zheng, W.C.; Xu, C.B.; Wei, R.F. Research progress of biochar injection into blast furnace. *J. Iron Steel Res.* **2021**, *33*, 1–8.
60. Xu, R.S.; Zheng, H.; Wang, W.; Jiang, X. Effect of carbonization temperature on microstructure of bamboo charcoal for blast furnace injection. *J. Iron Steel Res.* **2018**, *30*, 515–522.
61. Jiang, Y.Y.; Zheng, L.; Liu, Z.L. Effect of co-injection of biomass fuels on combustion rate. *Sichuan Metall.* **2019**, *41*, 18–21.
62. Wijayanta, A.; Alam, S.; Nakaso, K.; Fukai, J.; Kunitomo, K.; Shimizu, M. Combustibility of biochar injected into the raceway of a blast furnace. *Fuel Process. Technol.* **2014**, *117*, 53–59. [[CrossRef](#)]
63. Wang, C.; Larsson, M.; Lövgren, J.; Nilsson, L.; Mellin, P.; Yang, W.; Salman, H. Injecting solid biomass products into blast furnaces and their potential impact on integrated steel plants. *Energy Program. Energy Program* **2014**, *61*, 2184–2187.
64. Mathieson, J.G.; Rogers, H.; Somerville, M.; Ridgeway, P.; Jahanshahi, S. The use of biomass in the steel industry—Australian perspective. In Proceedings of the 1st International Conference on Energy Efficiency and CO₂ Reduction in the Steel Industry (EECR Steel 2011), Dusseldorf, Germany, 27 June–1 July 2011.
65. Wang, G.W.; Zhang, J.L.; Jui, Y.L.; Mao, X.M.; Ye, L.; Xu, W.R. Hydrothermal carbonization of corn stover for hydrochar production and its injection into blast furnaces. *Appl. Energy* **2020**, *266*, 114818. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.