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Review

The Application of Lignocellulosic Biomass Waste in the Iron and Steel Industry in the Context of Challenges Related to the Energy Crisis

Anna Biniek-Poskart [1], Marcin Sajdak [2], Magdalena Skrzyniarz [3], Jakub Rzącki [3], Andrzej Skibiński [1] and Monika Zajemska [3,*]

[1] Faculty of Management, Czestochowa University of Technology, 19 B Armii Krajowej Ave., 42-200 Czestochowa, Poland; a.biniek-poskart@pcz.pl (A.B.-P.); andrzej.skibinski@pcz.pl (A.S.)
[2] Department of Air Protection, Faculty of Energy and Environmental Engineering, Silesian University of Technology in Gliwice, 44-100 Gliwice, Poland; marcin.sajdak@polsl.pl
[3] Faculty of Production Engineering and Materials Technology, Czestochowa University of Technology, 19 Armii Krajowej Ave., 42-200 Czestochowa, Poland; magdalena.kocyba@pcz.pl (M.S.); jakub.rzacki@pcz.pl (J.R.)
* Correspondence: monika.zajemska@pcz.pl

Abstract: This review presented a comprehensive analysis of recent developments in research regarding the use of lignocellulosic biomass products in the iron and steel industry. The role of lignocellulosic biomass used as a source of energy as well as reducing agents in iron and steel sector in the era of energy crisis served as the foundation for this review. Attention has been paid to different biomass characteristics as well as pretreatment methods and conversion products of biomass. The present review also included some issues of energy management system in the steel industry. Furthermore, the possibilities of replacing fossil energy carriers with lignocellulosic biomass in the steel and iron industry was reviewed focusing on advantages, challenges, and future prospects. The present process and product quality criteria, which biomass-derived fuels must also meet, was discussed. This paper compiled the most current developments in biomass metallurgical research to serve as a source for the theoretical foundation as well as for the development of practical applications. The novelty of this study lies in the comprehensive discussion of the lignocellulosic biomass application in the iron and steel industry that are so far unpublished.

Keywords: iron and steel industry; lignocellulosic biomass; biomass waste management; energy management; thermal processing

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Citation: Biniek-Poskart, A.; Sajdak, M.; Skrzyniarz, M.; Rzącki, J.; Skibiński, A.; Zajemska, M. The Application of Lignocellulosic Biomass Waste in the Iron and Steel Industry in the Context of Challenges Related to the Energy Crisis. *Energies* **2023**, *16*, 6662. https://doi.org/10.3390/en16186662

Academic Editors: Adrian Ilinca and Abdul-Ghani Olabi

Received: 30 June 2023
Revised: 12 September 2023
Accepted: 15 September 2023
Published: 17 September 2023

1. Introduction

The current state of affairs in the energy sector raises global concerns as well as forces people and nations to diminish the use of fossil fuels and save energy. In the coming years, problems with the availability and high prices of coal, oil, and natural gas for the energy, heating, and steel industry are anticipated. That situation could, of course, be the result of less extraction of this raw material and disconnection of the supply chain from the east. The conflict between Russia and Ukraine has led to various disturbances, and one of the most important areas of its impact is the energy market. The crisis that affected this market is a derivative of the European Union's high dependence on supplies of Russian energy resources, without which no economy is able to function. This situation, caused by unprecedented inflation and skyrocketing fossil fuels prices, has had a serious impact on public infrastructure, as well as industrial and private recipients, prompting decision-makers to discuss changes in the rules of operation of European electricity markets. In addition, coal futures prices are expected to increase due to the anticipated sanctions on coal imports from Russia. The prices of futures contracts, which were record high in 2022, reflect the price for the next year, due to threats regarding a possible shortage of generation capacity, or owing to future natural gas prices.

The energy crisis has also inevitably left its mark on the metallurgical sector steel producers in Europe have been compelled to a halt or to reduce production due to rising energy prices as reported by the Reuters. The second largest steelmaker in the world, ArcelorMittal, has also shut down a blast furnace in Germany, France, Spain, and Poland. It predicts that its 25% output in Europe would be around 17% lower than a year ago. Even though the eastern Belgian facility of stainless steel manufacturer Aperam boasts four wind turbines and more than 50,000 solar panels, work has been halted due to rising energy costs [1]. Concurring with the most recent press reports, the current circumstances may have a critical effect on the course of the change leading to expediting the resignation from traditional fossil fuels in Europe as well as in the world.

The steel sector is regarded as a high user of carbon and fossil fuels. In general, there are four different routes in steel production: BF-BOF, i.e., blast furnace/basic oxygen furnace; EAF, i.e., melting of scarp in an electric arc furnace; DRI-EAF, i.e., direct reduction/electric arc furnace, as well as SR-BOF, that is smelting reduction/basic oxygen furnace [2], which is shown in Figure 1.

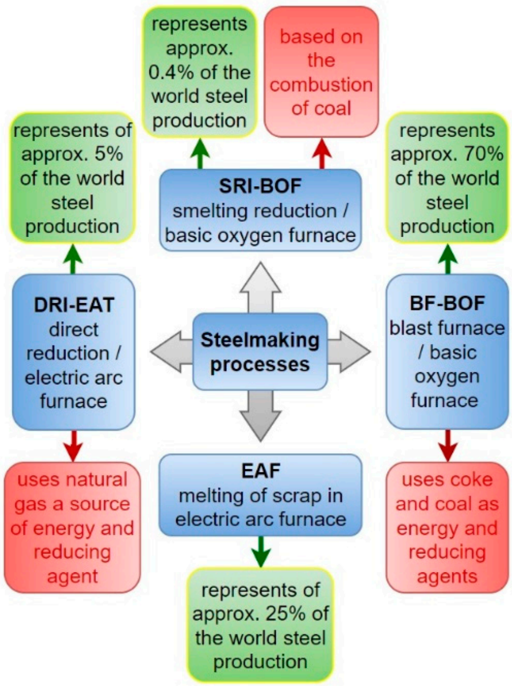

Figure 1. Four main routes of steel production [2].

Metalworking processes require extremely high temperatures, which makes them among the industry's most energy-intensive processes. One steelworks needs more energy than an agglomeration of one million people [3]. Only in production facilities for the preparation of raw materials, about 80 kg of fossil coal are used for every ton of utilized output. Per ton of sinter output, the sintering machine uses around 50 kg of fossil fuel [4]. Electric or oxygen processes are used to make steel, whereas the oxygen route consumes a huge amount of fossil fuels and, hence, generates significant emissions of CO_2. According to the data that are currently available, it is estimated that global steel manufacturing accounts for 5–6% of all greenhouse gas emissions [5]. According to Shukla [6], typically, 0.8 tons of coal are needed to produce 1 ton of crude steel, while 1 ton of hot metal produced in a coke blast furnace leads to 1.9 tons of CO_2 emissions. The metallurgical industry is inclined to search for new solutions in the field of energy production based on energy carriers other than fossil fuels for yet another reason, which is ecology and the pursuit of sustainable development. Iron and steel production are crucial to economic growth, but they are also the leading industrial source of CO_2 emissions. As the World Steel Association claimed in 2022, 1878.5 Mt of crude steel were produced globally. According to the same group, the demand for steel would increase by 2.2% to 1881.4 Mt in 2023 [7]. The International Energy Agency (IEA) [8] reports that steel has a carbon footprint of 1.4 tons per ton produced, whereas McKinsey and the World Steel Association place that number at 1.85. This is a weighted average of the two primary global steel manufacturing processes. The "primary" and "secondary" methods are generally referred to as the route of BF-BOF, i.e., blast furnace-basic oxygen furnace as well as EAF, i.e., the electric arc furnace. These two technologies have respective CO_2 footprints of 1.987 and 0.357 tons per ton of steel produced. However, in rare instances, the amount of CO_2 produced per metric ton of steel might reach 3. The variations amongst steel producers can be substantial. It all depends on how the steel is made, and it appears that the figures given above are an average of two separate production processes [9].

According to the report elaborated in cooperation with World Bank [10], the European Green Deal, i.e., Europe's new growth strategy, intends to reduce pollution, make industry and transportation sustainable, achieve climate neutrality in Europe by 2050, and grow the economy through green technologies, which may become a development impulse for the industry, including the steel industry. A promising and viable alternative approach to implement European Green Deal is to employ biomass products in the iron and steel industry as a source of energy as well as reducing agents. Recently, new and improved existing solutions for the use of biomass in the iron and steel industry have been sought. Lignocellulosic biomass is regarded by Yadav et al. [11] as an abundantly accessible renewable feedstock for the generation of biofuels that has the potential to minimize reliance on petrochemical refineries. In contrast to other bioresources, lignocellulosic waste is unique due to its quantity, renewable status, biodegradability, and biocompatibility. However, the limited solubility and processability of natural lignocellulosic materials reduce their use. Thus, pretreatment is necessary to utilize it later as an energy source or renewable resource. Physical or mechanical pretreatment, such as milling, grinding, or chipping, is the first step in processing lignocellulosic biomass. It aims to break the complex structure of lignocellulosic biomass. Chemical pretreatment, on the other hand, entails the pretreatment of various lignocellulosic feedstock types employing a range of chemical agents, including acids, ammonia, alkalis, ozone, peroxide, deep eutectic solvents, and ionic liquids [12,13].

A great deal of work has been carried out over the years to investigate the use of biomass-based materials as a fuel and reductant in primary metal production in the place of fossil fuel carbon sources. In addition to being CO_2 neutral, biomass material is also probably lower in S, Cl, N, as well as other heavy metals, which are detrimental to the environment, human health, and metal quality [5]. One way to achieve a green low-carbon iron and steel industry is to replace conventional fossil fuels with biomass energy. In addition, it is also important to accelerate the adaptation of the industry's energy structure to modern, future-oriented technologies [14]. Thus, the demand for investments that boost energy efficiency will rise in the nearest future. The study presented in this paper was focused on biomass applications as a fuel source replacing coal during metallurgical processes.

The novelty of this study lies in the comprehensive discussion of the lignocellulosic biomass application in the iron and steel industry that are so far unpublished. The previous, scarce research and the literature gap on the use of lignocellulosic biomass in the iron and steel industry and the current world energy crisis prompted the authors of the article to conduct a literature review in this topic. When we reviewed the literature, we found that there are not many papers that describe in detail replacing coke with charcoal from lignocellulosic biomass, and there are not much data on the specifics of the charcoal that is utilized.

2. The Role of Lignocellulosic Biomass in the Era of Energy Crisis and Decarbonization

The increasing need for energy is accompanied by the depletion of its conventional supplies, namely fossil fuels (coal, oil, and natural gas), and the consequent rise in environmental degradation. The usage of energy from renewable sources has grown in popularity as a result of these causes. Biomass is thought to be a promising renewable energy source. The use of substitute fuels from conventional fossil fuels is highly important, in view of the fact that iron and steel are among the world's largest energy-consuming and greenhouse-gas-emitting industries. The application of lignocellulosic biomass in the steel and iron industry has the potential to accelerate the transition of this sector to a low-carbon and environmentally friendly future by lowering the emissions of CO_2 and the consumption of fossil fuels. Biomass metallurgy is the name given to metallurgical processes that employ carbon and hydrogen-rich renewable biomass as the primary energy source and reducing agent to recover metals [14].

The possibilities of using alternative renewable sources as fuels in the various processes of the iron and steel industries have been examined in a number of studies [6,15–17]. Biomass can be used in such steelmaking processes, e.g., in the blast furnace, coke-making, and sintering. Various steelmaking techniques were addressed together with current advancements toward partial or complete replacement of fossil fuels by renewable energy based on biomass. Kieush et al. [4] showed the potential of employing secondary carbon bio-carriers, i.e., biomass, biochar, torrefied biomass, biocoke, or charcoal for iron and steel production. The four main routes of steel production, namely the melting of scrap in an electric arc furnace (scrap/EAF), blast furnace/basic oxygen furnace (BF/BOF), smelting reduction/basic oxygen furnace (SR/BOF), and direct reduced iron/electric arc furnace (DRI/EAF) were described in their work.

To achieve a reduction in the demand for fossil fuels and low CO_2 emission targets, a change in the ways that energy is produced and consumed is necessary. Biomass metallurgy has the advantage of being carbon neutral and reducing CO_2 emissions significantly when compared to traditional coal metallurgy [14]. Biomass can, under the correct circumstances, be viewed as a carbon-free resource, making it a desirable choice for lowering emissions from the manufacture of iron and steel. According to the IEA's bioenergy program, if produced sustainably, bioenergy can be carbon neutral within the biospheric carbon cycle due to the fact that the carbon being released during combustion has already been removed from the atmosphere and will be removed once more as the plants regrow. Furthermore, after transformation, the physicochemical properties of biomass can be comparable to those of coal. Because of its high carbon content, which ranges from 39 to 57%, lignocellulose biomasses in particular seem to be a promising, sustainable, and cost-effective solution. A remarkable opportunity exists to develop alternative fuels as a replacement for fossil fuels thanks to readily available, affordable, and renewable lignocellulosic biomass, especially when talking about a significant part of agricultural waste, which is underutilized and inadequately handled. For instance, in Nigeria, approx. 30% of agri-food wastes produced per year are left after harvest without any further application.

2.1. Biomass Characteristics

Growing interest has been shown in recent years in creating pyrolysis routes from lignocellulosic biomass to produce biofuels. Plant material known as lignocellulosic biomass is not employed in food or animal feed [18]. Lignocellulosic biomass is the most energy-efficient type of biomass because lignin and cellulose are characterized by a large share of "waste" mass, which is suitable for use as a source of thermal energy. It mostly comprises yard trimmings, energy crops, forestry waste, and agricultural waste. After coal and petroleum products, lignocellulosic biomass is considered as one of the largest source of energy. It is one of the best possibilities for the manufacturing of chemicals and fuel intermediates because of its widespread availability around the globe, low cost, and minimal greenhouse gas emissions [19,20]. More than 200 billion tons of lignocellulosic biomass is thought to be produced annually on Earth. Lignocellulosic biomass mostly comprises lignin (15–25 wt%), hemicellulose (20–40 wt%), and cellulose (30–50 wt%) [21]. Ash, lipids, and proteins make up the remainder of lignocellulosic biomass. Depending on the species, lignocellulosic biomass can have different chemical and elemental compositions. The primary factor in determining the overall calorific value of a substance is its carbon content, which accounts for 34.1 to 53.5 weight percent of the biomass. In comparison to fossil fuels, the nitrogen (1.8 wt%) and sulfur (0.1–0.6 wt%) concentrations of biomass are often rather low [22]. Given that each fraction travels through a separate set of decomposition routes under a different set of reaction circumstances, the relative quantity of the biomass component has a considerable impact on both the output of biomass products and their chemical composition [23].

Raw biomass has a number of drawbacks, including a low calorific value, high moisture content, high oxygenated volatile materials (VM) content, hygroscopic character, and low energy density, varying composition and properties or contamination when low quality sources are used. While VM can range from 63 to 88 weight percent, the fixed carbon (FC) content of raw biomass typically ranges from 9 to 25 weight percent [4,24,24]. A higher volatile matter concentration causes ignition to be quicker and easier with a lower ignition temperature than coal. It offers improved combustion, but because it burns quickly, some unburned carbon ends up as ash. Additionally, a higher VM produces flammable vapors that are difficult to manage and useless for sintering operations until additional preparations are made [25]. Biomass has an energy density that is between 10 and 40% lower than that of coal, and its heating value is around half that of coal [26]. On the other hand, as reported by Jha et al. [26], in comparison to coal, biomass has less sulfur, which lowers SO_x emissions. Moroń et al. [27] studied the impact of fuel sulphur content in blends of coal with biomass on the conversion into SO_2. They noticed that the emissions of SO_2 were drastically decreased by mixing biomass with coal. Furthermore, a higher content of volatile matter in biomass ensures easier, more rapid ignition, as well as lower ignition temperature. An interesting result of studies was presented by Mahanta et al. [28] that concern blending high sulfur low-rank North East Indian coal with biomass of Acacia as an additive in order to reduce the amount of sulfur and the ash content as well as to enhance the combustion performance. The addition of biomass appears to improve coal's ignition and burnout characteristics because to its improved reactivity and greater volatile release at lower temperatures. However, the moisture content, which lowers the heat value, is the main flaw of biomass. The moisture content of biomass typically ranges from 3% to 63%, although it can reach 91%. Because biomass mostly consists of organic materials generated from plants and crops, it has a greater moisture content. Since biomass has lower levels of nitrogen and sulfur, it produces fewer emissions of NO_x and SO_x. According to Dubinin et al. [29], biomass generally has 10 times less sulfur than coal and coke. The properties of different types of biomass are described in Table 1.

Table 1. Comparison of physicochemical properties of biomass.

Biomass	Ultimate Analysis (%)					Proximate Analysis (%)				Source
	C	H	N	S	O	M [1]	VM [2]	FC [3]	A [4]	
Rice straw	36.2–47.46	5.2–6.44	0.7–0.83	-	40.3–45.15	4.98	81.54	16.46	10.82–17.6	[30]
Wheat straw	41.8–45.5	5.5–5.7	0.7–1.0	-	35.5–47.9	7.1	76.7	9.2	7.0	[30]
Barley straw	45.41	6.1	1.18	-	46.21	4.90	78.8	11.83	6.43	[30]
Corn straw	45.75	5.93	0.94	0.11	43.69	4.21	-	-	5.91	[30]
Sugarcane straw	41.88	5.87	0.47	-	41.72	3.12	87.61	3.22	9.17	[30]

Table 1. *Cont.*

Biomass	Ultimate Analysis (%)					Proximate Analysis (%)				Source
	C	**H**	**N**	**S**	**O**	**M** [1]	**VM** [2]	**FC** [3]	**A** [4]	
Rape straw	42.21	5.54	0.42	0.07	51.76	-	-	-	3.69	[30]
Mustard straw	54.46	6.29	0.5	-	38.75	3.99	75.55	15.44	5.02	[30]
Moringa husk	48.84	6.53	-	-	-	1.47	76.6	-	2.36	[31]
Eucalyptus husk	50.1	5.42				5.77	68.73		2.43	[31]
Sugarcane bagasse	46.4	4.68	-	-	-	7.03	75.03	-	4.33	[31]
Elephant grass	40.0	5.36	-	-	-	0.1	69.95	-	13.5	[31]
Rice husk	43.4	4.33	-	-	-	0.1	73.18	-	9.55	[31]
Corn cob	45.5	6.7	-	-	-	0.79	81.31	-	1.16	[31]
Corn straw	44.8	6.8	-	-	-	0.31	81.68	-	1.58	[31]
Oil palm tree trunk	40.75	6.47	0.51	-	-	-	-	-	-	[32]
Mesocarp fibers	45.2	9.04	3.12	0.1	42.53	-	75.23	18.42	5.35	[33]
Palm kernel shells	46.3	5.72	0.7	0.64	47.6	9.4	69.8	16.8	4.0	[34]
Hazelnut shells	50.3	6.3	0.7	-	43.2	9.0	76.7	22.5	0.8	[35]
Switch grass	43.2	5.89	0.52	0.16	50.23	6.25	71.21	19.14	3.4	[36]
Rice straw	37.18	5.81	0.62	-	56.39	9.8	76.32	9.08	13.91	[37]
Coconut shell	48.6	5.97	0.62	1.09	43.8	10.5	71.1	17.6	0.8	[34]
Pine Sawdust	49.5	7.1	0.5	-	42.8	5.0	84.5	15.4	0.1	[35]

"-" denotes not detected/not reported; [1] moisture; [2] volatile matter; [3] fixed carbon; [4] ash.

Due to the raw biomass's low calorific value, high moisture and oxygen content, and extremely changeable composition and characteristics, the direct conversion of biomass into energy is not very profitable [38,39]. Therefore, techniques for increasing the energy characteristics of biomass are actively being investigated.

2.2. Methods of Biomass Conversion

It would be ideal to create items that either outperform current fuels and/or reductant technologies or reduce any physical flaws. Thus, effective methods of biomass conversion are required to create chars that are chemically equivalent to coal or coke. In order to obtain bio-substitutes with qualities permitting a complete or at least partial substitution of fossil fuels in metallurgical processes, pre-treatment is, therefore, necessary. To improve the fuel characteristics, increase the heating value, and to apply to various plants in the iron and steel sectors, agricultural waste can be thermochemically converted into biochar, bio-oil, and syngas [6]. Thus, thermal processing such as torrefaction [40,41], pyrolysis [42,43], gasification [44], liquefaction [45,46], or hydrothermal carbonization [47–49] can be applied. Promising results of lignocellulosic biomass thermochemical processes [50] were achieved by the authors, especially in the case of torrefaction [51,52], pyrolysis [20,53,54], and gasification and co-gasification [55–57].

Figure 2 shows methods of conversion of biomass through modern and traditional way as well as products generated during these processes. Furthermore, typical applications of biochar were also presented. In turn, Table 2 constitutes a compilation of individual processes and their main characteristics.

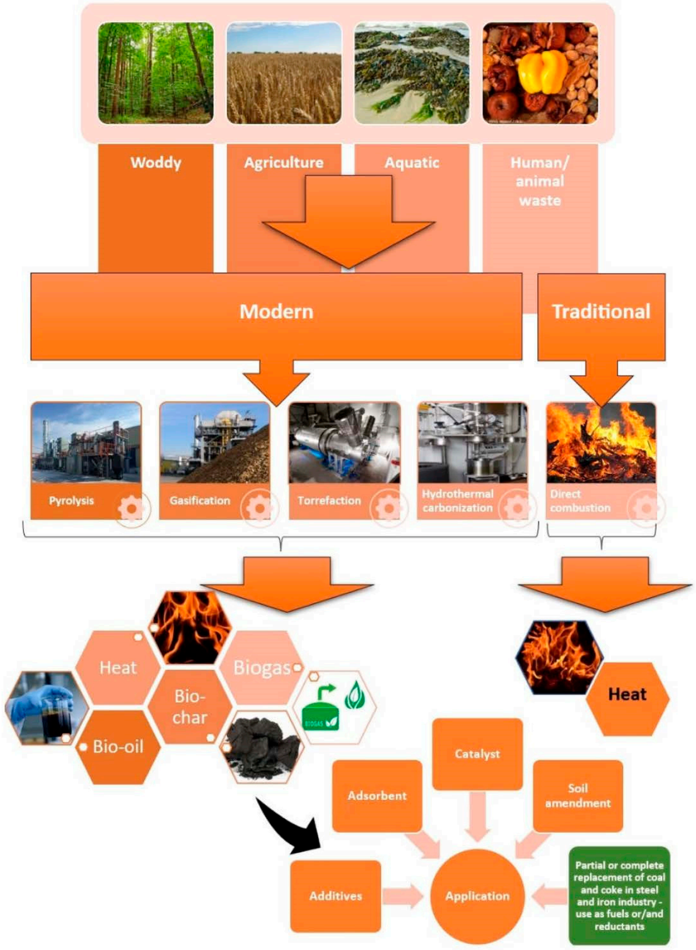

Figure 2. Methods of conversion and use of biomass and its products [58–63].

Table 2. Compilation of characteristics of individual processes.

Process	Reaction Temperature °C	Conditions	Product	Composition of Product (m-%)			Source
				Solid	Liquid	Gas	
Pyrolysis, slow	180–480	Residence time: 15 min to even several hours; absence of air (oxygen)	Biochar	>60	25–30	10–15	[64–67]
Pyrolysis, fast	Above 500	High heating rate [68]; for a few seconds; absence of air	Bio oil	20–30	30–70	20–30	[68–71]
Gasification	600–1400	With the use of oxidizing agent; under higher pressure (1–5 MPa)	Synthesis gas	10	5	85	[66,72,73]
Torrefaction	200–350	For 15–30 min without presence of air	Biochar	80	15	5	[52,74,75]

Table 2. *Cont.*

Process	Reaction Temperature °C	Conditions	Product	Composition of Product (m-%)			Source
				Solid	Liquid	Gas	
Hydrothermal Carbonization	160–250	Mixed with saturated water-steam; from a few minutes to even few hours	HTC Carbon	50–80	5–20	2–5	[66,72,76]
Combustion	Wide range depending on the fuel type	With air excess	Heat	-	-	-	[72]

The thermochemical process of pyrolysis, which can result in the production of pyrolytic gas, biochar, and bio-oil, typically occurs at temperatures within the range between 400 and 1000 °C and without access to air [77]. Slow pyrolysis produces charcoal primarily, and calls for a slower heating rate, lower temperature, and a longer residence period. In contrast, bio-oil is the primary end product of fast pyrolysis, which is carried out at a rapid heating rate and for a brief period of time [78]. Fast pyrolysis is the process of rapidly heating biomass to high temperatures without the presence of air, more precisely without oxygen. It takes place at high temperatures between 300 and 700 °C, with a quicker heating rate of 10 to 200 °C/s, a brief solid resistance duration of 0.5 to 10 s, and feedstock with a tiny particle size (1 mm) [79]. Pyrolysis and gasification are both thermochemical processes, although gasification takes place at much higher temperatures of around 1000–1400 °C and in the presence of less oxygen [77].

To enhance the qualities of raw biomass, light, medium, or severe torrefaction can be used depending on the intended final attributes of the solid product. Torrefaction is one of the most promising methods of biomass valorization. It typically takes place at temperatures between 200 and 350 °C, under atmospheric pressure, with inert gases present, and with residence times between 15 min and 3 h (depending on the kind of reactor and the parameters of the raw material) [41,80,81]. Torrefaction produces solid (biochar), liquid, and gaseous byproducts. The solid material (the so-called torrefied/carbonate) constituting approx. 80% has a hydrophobic character and a uniform structure, with a low moisture content, increased regrindability, low bulk density, and high calorific value. Thanks to the torrefaction process, biomass gains new properties that are particularly beneficial when used for energy purposes. By altering the shape, eliminating water and oxygen through carboxylation and dehydration processes, as well as damaging the fibrous structure of biomass, the primary goal of this process is to enhance the qualities of the biomass. Torrefaction eliminates most of the disadvantages of biomass. Torrefied biomass acquires unique physical–chemical characteristics that are particularly advantageous when utilized as a fuel for energy production, such as during combustion. The biomass is heated and partially devolatilized during torrefaction. It loses bulk while maintaining its energy level. The majority of the unfavorable characteristics of biomass are eliminated during the torrefaction process, resulting in the production of fuel with a greater carbon content, a higher calorific value, a higher energy density, improved grindability, hydrophobicity, and resistance to biodegradation. As a result, it may be possible to lower the cost of managing, storing, and transporting biomass [52]. Torrefaction is a less aggressive heat-treatment method than pyrolysis, which enhances the characteristics of biomass without harming the high molecular components. Torrefied biomass also contains less ash than biochar produced during the pyrolysis process. Torrefaction can also contribute to the minimization of carbon dioxide emissions, which is less by approx. 50 kg/t of steel. Furthermore, the distribution of biomass constituents is altered by the torrefaction process. At temperatures between 200 and 900 °C, lignin slowly breaks down. In turn, cellulose and hemicelluloses begin to break down at temperatures between 200 and 400 °C. Torrefaction lowers the amount of hemicellulose from 22% to 4.6% at 300 °C while progressively destroying the cellulose and increasing the amount of lignin. As a result of torrefaction, biomass slowly decomposes, dries up, and simultaneously releases a small amount of volatile organic chemicals. This leads to changes in the torrefied biomass composition. The hydrogen and oxygen contents of torrefied biomass are lower, while the carbon content is higher [4]. Furthermore, because raw biomass has such a high percentage of active ingredients (hemicellulose and cellulose), it often exhibits characteristics of high reactivity and low thermal stability, which indicate a significant danger of unprompted combustion and deterioration during storage and transit. It has been demonstrated that biomass hydrophobicity and fuel quality may be improved with torrefaction pretreatment, which also lowers the likelihood for spontaneous combustion [82]. The torrefied biomass can either be pumped into the BF or utilized directly in the synthesis of carbon composite agglomerates (CCAs), coke, and sinter. Secondary carbon bio-carriers might be used to produce biocoke when the characteristics are altered. Based on the requirements for the carbon-containing material in a specific process, the torrefied biomass can make up anywhere from 3 to 50 weight percent of the feed mixture during the coke-making process. The biocoke that is produced can be used for: sintering iron ores to serve as fuel; BF to perform duties as a fuel and reducing agent; EAF for slag foaming and carburizing; a melter gasifier to produce heat; and serve as a reducing agent [4].

2.3. Biomass Conversion Products

Combustion, torrefaction, slow pyrolysis, quick pyrolysis, and gasification are the primary thermochemical biomass conversion processes. Torrefied biomass, biochar, non-condensable gases (NCG), condensable gases (bio-oil; recovered from pyrolysis gas by cooling), and syngas are the many byproducts. The amount of each conversion product and the percentage of each fraction vary depending on both the procedure in issue and the process parameters [67].

As presented in the report developed by the Technical Research Centre of Finland (VTT) [67], depending on the conversion rate under consideration, there are several potential end applications for the conversion products:

- Torrefaction reduces the surplus oxygen content of the biomass and increases the energy density. Torrefied biomass might be utilized in place of fossil fuels in many combustion applications, such as the production of electricity [75,83,84].
- For wet biomass (or sludge), hydrothermal carbonization is normally carried out in pressured autoclaves at temperatures within the range of 200 and 300 °C. The process purges the solid mass of inorganic chemicals that are water soluble. The product possesses heating properties that are comparable to those of torrefied biomass and a relatively low carbon-to-oxygen ratio [48,66,85,86].
- Slow pyrolysis optimizes the yield of biochar, which may be utilized either directly or after additional processing in a variety of applications, such as replacing coal in combustion, acting as a bio-reducer in the production of metals, enhancing soil, treating water, etc. Condensable and non-condensable hot pyrolysis gases are also produced, and these gases may be used as fuel to substitute fossil-based combustibles in a variety of applications. Bio-oil may be made by collecting the condensable portion [87–90].
- Fast pyrolysis enhances the output of condensable gas-derived bio-oil. Additionally, a small quantity of biochar as well as some NCG are produced. When compared to those produced by slow pyrolysis, the characteristics of biochar are somewhat different, which might limit its potential applications, such as a bio-reducer [91–93].
- In the process of gasification, biomass hydrocarbons completely devolatilize into syngas when enough oxygen is present. CO, CH_4, H_2, CO_2, and smaller quantities of other gases are the main constituents. Syngas can be utilized in combustion to produce hydrogen, Fischer–Tropsch gasoline, Fischer–Tropsch diesel, alcohols, olefins,

oxo compounds, synthetic natural gas (SNG), and ammonia, or as an intermediate product for those processes [44,94,95].

The origin of the biomass on which biochar is based determines its features, and even different tree species will create biochar with variable qualities. The density, strength, and porosity of the biochar, for instance, will be influenced by the density of the tree species. As a result, in order to attain superior qualities, the biochar that is now utilized in the metallurgical sector (in the manufacture of silicon and ferrosilicon) is based on hardwoods. The solid carbon is crucial for metallurgical operations since the carbon that is gassed off throughout the process will not function as a reducing agent. The process parameters that are employed to produce biochar have a significant impact on the yield of solid carbon. A relatively low yield of fixed carbon is normally obtained from traditional charcoal manufacture. When the gaseous tar components spend a longer time in and around the charcoal, the yield can be greatly improved. Compression and densification can boost the tensile strength of biochar. Fuel sources such as coal and biomass come in a wide variety. Energy levels, organic and inorganic contents, and physical qualities are where these variances are most noticeable [96–98]. Nonetheless, the properties of biochar obtained during torrefaction or pyrolysis are more comparable to coal. However, contrary to biochar, which normally has a highly porous structure due to volatiles releasing during the charring process, coals typically have a densely packed structure [99]. The characteristics of different types of torrefied biomass and coal are presented in Table 3.

The results of the computer simulations performed within work [20] allowed the estimated calorific value of the pyrolysis gas to be calculated, which ranged from 20.61 to 25.19 MJ/m^3. The high calorific value of gas promotes its further usage in the steel and heating sectors. It is possible to co-combust natural gas with the gas produced by the pyrolysis of lignocellulosic waste, which will result in a reduction in natural gas consumption. The aforementioned information demonstrates that pyrolysis gas may be a great substitute for traditional fuels, while also advancing environmental protection efforts and playing a significant part in the circular economy for biomass. The reduced moisture and oxygen content, as well as an increase in the calorific value and carbon fraction of the solid product, are benefits of thermal biomass treatment that make it more suited to be utilized in several metallurgical processes. However, after being heated, the ash content of biochar increases and its mechanical strength decreases. Numerous studies have concentrated on the use of biochar for metallurgical processes after pyrolysis at temperatures ranging from 350 to 1100 °C. The solid product reduction, which is the most useful for application in subsequent metallurgical operations, is a drawback of high-temperature pyrolysis.

Table 3. Physicochemical properties of coal and biochar from biomass.

Component		**Proximate Analysis, wt.%**				**Ultimate Analysis, wt.%**						**Source**
		M [1]	A [2]	VM [3]	FC [4]	S	C	H	N	O	P	
Coal A		1.5	11.0	30.3	58.7	0.68	75.38	4.77	1.54	6.63	-	[100]
Coal B	Subbituminous	16	6.5	29.5	-	0.65	-	-	-	-	0.06	[101]
Coal C	High-VM	2.5	9.0	34.5	-	0.40	-	-	-	-	0.01	[101]
Coal D	Semianthracite	1.5	7.5	12.5	-	0.60	-	-	-	-	0.07	[101]
Coal E	Anthracite	2.0	9.0	6.5	-	0.50	-		-	-	0.01	[101]
Coal F		1.4	11.0	33.6	55.4	0.82	74.49	5.09	1.61	6.99	-	[100]
Coal G		3.8	8.4	23.2	68.4	0.32	82.61	4.78	1.43	2.46	-	[100]
Biochar A	Torrefied softwood	2.0	0.5	69.1	-	0.02	-	-	-	-	0.01	[101]
Biochar B	Semicharcoal (hardwood)	0.7	2.3	33.1	-	0.05	-	-	-	-	0.07	[101]
Biochar C	Charcoal (softwood)	1.0	0.9	6.2	-	0.05	-	-	-	-	0.02	[101]
Biochar D	Charcoal (hardwood)	1.8	3.4	7.6	-	0.09	-	-	-	-	0.10	[101]
Biochar E	Charcoal (mallee)	1.6	3.4	0.3	-	0.04	-	-	-	-	0.0	[101]
Biochar F	Biocoke	0.65–1.35	5.8–10.8	1.4–2.7	87.8–92.4	0.22–0.2	86.38–91.65	-	-	-	-	[4]
Biochar G	Charcoal	0.63	7.73	25.8	-	-	69.7	3.2	-	-	-	[31]
Biochar H	Torrefied sugarcane bagasse	1.41	2.52	78.74	17.33	-	40.0	6.74	0.72	52.54	-	[102]
Biochar I	Torrefied eucalyptus	-	-	-	-	-	56.01	5.99	0.05	36.18	-	[103]
Biochar J	Chlorella sp.	2	12.8	32.4	-	2	35	9.2	3	2.5	-	[104]
Biochar K	Sargassum sp.	2.5	14.2	35	-	2.6	61.5	4.2	2	28	-	[104]
Biochar L		2.30	0.57	19.10	91.6	0.02		2.27	0.38	1.95	-	[105]

Table 3. *Cont.*

Component		Proximate Analysis, wt.%					Ultimate Analysis, wt.%					Source
		M [1]	A [2]	VM [3]	FC [4]	S	C	H	N	O	P	
Biochar M	Safflower seed cake	-	8.20	20.00	7180	-	70.43	3.43	3.36	22.39	-	[106]
Biochar N	Concarpus waste	-	5.27	-	-	-	76.83	2.83	0.87	14.16	-	[106]
Biochar O	Rice straw	7.20	15.40	62.40	14.90	-	44.80	5.10	0.90	49.20	-	[106]
Biochar P	Pitch pine	-	7.90	-	-	-	70.70	3.40	0.60	25.50	-	[106]
Biochar R	Pine sawdust	5.00	0.30	77.70	16.90	-	50.30	6.70	0.20	42.70	-	[106]
Biochar S	Spruce woodchips	-	31.00	-	-	-	74.80	0.14	0.15	4.20	-	[106]
Biochar T	Corn stovers	2.3	58.00	12.70	28.70	-	33.20	1.40	0.81	8.60	-	[106]
Biochar U	Coconut shell	4.4	0.70	80.20	22.00	-	50.20	5.70	0.00	43.40	-	[106]
Biochar W	Peanut shell	1.90	7.80	8.10	82.20	-	93.61	1.99	1.05	3.35	-	[106]
Biochar X	Pine cone	1.20	4.70	6.70	87.40	-	95.16	2.63	1.61	0.60	-	[106]
Biochar Y	Peanut hull	-	9.30	18.10	-	-	81.80	2.90	2.70	3.30	-	[106]
Biochar Z	Switch grass	-	7.80	13.40	-	-	84.40	2.40	1.07	4.30	-	[106]
Biochar AA	Pongamia glabra deoiled cake	4.30	11.60	14.60	69.50	-	75.00	3.26	5.00	12.58	-	[106]
Biochar AB	Jute dust	9.44	10.78	15.07	64.71	-	70.25	2.78	4.04	22.93	-	[106]
Biochar AC	Sugarcane bagasse	1.30	8.57	9.17	80.97	-	85.59	2.82	1.11	10.48	-	[106]
Biochar AD	Coco peat	2.55	15.90	14.30	67.25	-	84.44	2.88	1.02	11.67	-	[106]
Biochar AE	Palm kernel shell	0.00	6.86	12.29	80.85	-	87.85	2.91	1.11	8.14	-	[106]
Biochar AF	Cotton seed hull	6.53	7.90	18.60	67.00	-	87.50	2.85	1.50	7.60	-	[106]
Biochar AG	Soybean cake	1.50	16.80	10.10	71.60	-	83.95	1.48	8.32	6.25	-	[106]
Biochar AH	Sesame	3.40	36.80	22.00	37.80	-	86.64	3.10	6.93	3.09	-	[106]

"-" denotes not detected/not reported; [1] Moisture; [2] Ash; [3] Volatile matter; [4] Fixed carbon.

3. Lignocellulosic Waste and Energy Management in the Steel Industry

As reported by the Organisation for Economic Co-operation and Development in their report [107], typically, the iron and steel sector is the second-biggest user of energy among all industrial sectors. Approximately 20% to 25% of the steel plant's total input expenses are made up of energy expenditures. According to the technical report elaborated by the European Commission's science and knowledge service, the Joint Research Centre (JRC) [108], the energy expenses for EU27 plants are the third highest in the world (on average 17% of total production costs). Utilizing less energy while producing the same or even more is known as energy efficiency. It is becoming more widely acknowledged as one of the most significant and economical methods for lowering greenhouse gas (GHG) emissions produced during industrial operations, particularly those in the iron and steel industry. In reality, technological advancements in energy efficiency have the potential to cut industrial energy usage by around 20% [107]. It is significant to note that energy efficiency may raise a company's competitiveness and production in addition to saving energy and lowering GHG emissions. Along with enhanced internal efficiencies that boost the company's value, successful energy efficiency projects frequently have this effect. Identifying and prioritizing the complete spectrum of energy savings potential before making any other significant investment decisions requires the implementation of an energy management system, which is a crucial first step. As reported by McKinsey & Company experts and consultants [109] as well as Danish Energy Agency [110], better energy management, which often involves just operational improvements, has been demonstrated to enable businesses to save up to 10–30% of their yearly energy usage. As a result, operating expenses may be reduced in a manner comparable to that. Companies optimize their industrial systems and increase overall system efficiency monitoring by implementing an Energy Management System (EnMS) in order to improve energy performance. EnMS is known as a systematic method for continuously enhancing energy performance and maximizing energy savings. An EnMS's main goal is to motivate employees at all organizational levels to continuously regulate their consumption of energy. By creating a framework for industrial facilities to monitor their continuing energy usage and find possibilities to deploy energy-saving technology, an EnMS helps enterprises in the iron and steel sector achieve this. Enhanced production and capacity utilization, decreased resource consumption and pollution, and cheaper operation and maintenance expenses are some additional productivity advantages for businesses employing an EnMS. These advantages all promote value creation and, consequently, a company's competitiveness [107].

Energy consumption is a significant contributor to emissions in the iron and steel sector, making energy efficiency improvements a desirable way to cut both pollution and greenhouse gas emissions. A major potential to lower costs and hazards connected with measures linked to reducing the emissions of greenhouse gases and pollutants is to increase energy efficiency. In order to achieve the so-called "triple bottom line", which focuses on the social, economic, and environmental elements, energy efficiency might, thus, be a useful and productive technique. In the current context, investing in energy-efficient devices is a wise approach for managing steel and iron plants [111].

Different cycles, including heating, cooling, melting, solidification, and processing, are used in iron and steel factory operations. It is an industry that uses large amounts of energy. The decreased energy use of iron and steel plants is of particular importance. For the iron and steel sector to remain competitive, sustainable, able to reduce its environmental effect, particularly greenhouse gas emissions, and improve resource management, energy conservation is essential [111,112]. The worldwide steel sector has a strong interest in energy saving. Energy efficiency strategies and technology address this difficulty and have improved in cost-effectiveness over the past several years, which has been beneficial during periods of high and unpredictable energy costs and intense concern for environmental issues [113]. In periods of high-energy price volatility, improving energy efficiency is a significant approach to lower these expenses and generate predictable revenues. There are several chances for reducing energy consumption that may be accomplished at individual iron and steel mills in an economical way. At the process, component, facility, as well as organizational levels, iron and steel industries have access to a variety of energy-efficient technologies and methods [114,115]. The most crucial areas of control for the management of the steel mill in the current situation are the reduction in energy costs and the enhancement of energy efficiency. The steel industry has achieved incredible strides in energy conservation since the 1960s, with the average energy intensity per ton of steel produced falling from 50 GJ/ton in the 1960s to its current level of roughly 20 GJ/ton. This has been accomplished by increasing the effectiveness with which various energy sources are employed, by improving the energy efficiency of the processes used in steel plants, and by making efficient use of the various materials used in the manufacture of iron and steel [114,116].

In order to achieve outcomes for energy conservation and efficiency in the iron and steel factory, effective energy management procedures are required. Energy management practices offer several opportunities in the iron and steel industry, including [111,113,117]:

- A drop in the energy intensity per ton of crude steel;
- The adoption of good energy-use practices;
- Employing effective procedures for the recovery of heat and gas energy;
- Allowing plant management to create strategies to reduce the facility's energy intensity;
- Allowing plant management to prioritize investments that will have the most impact on energy efficiency.

In addition to energy cost reductions, increased energy efficiency might have additional advantages. They consist of [111,117]:

- Reduced company risks and susceptibility to variable energy costs;
- Enhanced productivity;
- Improved product quality and a shift to market sectors with higher added value;
- Decreased environmental compliance costs.

3.1. Replacing Fossil Energy Carriers with Biomass in the Steel Industry

Coal and coke are fossil fuels that serve as the iron and steel industry's primary energy sources. One of the potential methods to minimize the use of fossil fuels and to reduce CO_2 emissions is the partial replacement of coke and coal in blast furnaces with biomass. Products made from biomass can be used in place of fossil carbon for producing metal and processing in a number of ways. As reported by Hakala et al. [67], as well as Mousa et al. [2], biomass products can be used, for instance, in [67]: partial replacement of fuel injected into the blast furnace; cokemaking for the production of bio-coke; producing bio-composites and/or bio-briquettes by pelletizing and briquettetting; creating bio-sinter through the sintering process; the bio-recarburization of steel in a ladle furnace, as presented in Figure 3. The best materials for technology of bio-blast furnace are solid biomass products like torrefied wood pellets and charcoal with high calorific values as well as high content of carbon. Among other bio-products, charcoal has the largest fixed carbon content, the highest calorific value, and the least volatile matter [2].

Research performed by Mathieson et al. [118,119] concerning BF tuyere injectant replacement with pulverized coal was highlighted as the application with the most promising and biggest potential for CO_2 reduction. By lowering the blast furnace's gasification temperature and reducing the overall carbon consumption, the resultant bio-coke may be beneficial. Some ironmaking blast furnaces might cut CO_2 emissions by 15% by replacing 20% of the coke with biomass, according to estimates [120]. Even if these numbers are unlikely to be reached in the majority of situations, the size of the global steelmaking business means that even slight advancements would have a major influence. Mathieson et al. [118,119] also presented results of a typical EAF steelmaking operation's use of biomass-derived chars, which is shown in Figure 4.

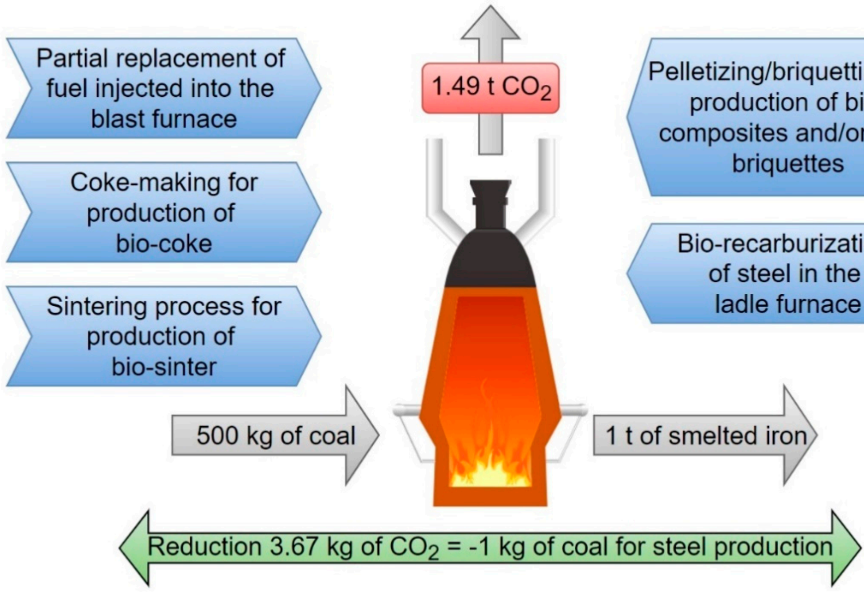

Figure 3. Main routes of replacing fossil energy carriers with biomass in the steel industry [2,67].

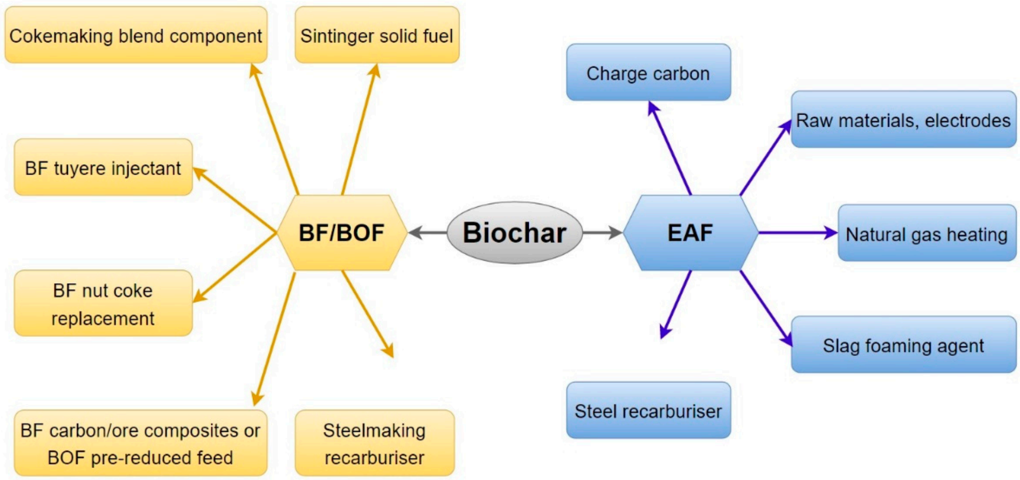

Figure 4. Applications for biochars within a typical integrated steelmaking operation and a typical EAF steelmaking operation [118].

Potentially, biochar might replace the pulverized coal that is now put directly into blast furnaces. Work has been carried out in this direction as part of the Australian CO_2 breakthrough initiative, which focused on using sustainable biochar in place of coal for pulverized coal injection (PCI) in the blast furnace. The manufacturing of charcoal is still being improved via development to increase its product criteria for steel manufacture. In the ArcelorMittal facility in Ghent, Belgium, the Torero partnership project is experimenting with using biocoal (torrefied waste wood) to partially replace coal [121]. While some blast furnaces do already run totally on biomass, these are smaller furnaces because of the relative strength of charcoal versus coke. Currently, particularly in Brazil, charcoal is utilized commercially to replace a portion of the coal applied in blast furnaces. Brazil is the global leader in production and consumption of biochar, of which approx. 75% of its production is applied in the steel industry [122,123].

3.2. Advantages of Using Biomass in the Steel/Iron Industry

Iron and steelmaking, as well as the smelting processes used to produce non-ferrous metals, both produce significant amounts of carbon dioxide (CO_2) that can be reduced by utilizing biomass as a carbon source rather than fossil fuels. Particularly this biomass, which can be recoverable from the expanding pulp industry side streams and biorefineries, might find a value-adding end application as a renewable raw material source for the metal manufacturing and processing sector [67]. With less investment and technical risk than other ground-breaking technologies in development, the use of fuels and reductants generated from biomass in the iron and steel-manufacturing industry offers a sustainable solution for lowering net CO_2 emissions. Because of its carbon neutrality, biomass cuts emissions. An efficient technique to lower GHG emissions might be to use biomass in the place of coke breeze during the sintering process. Numerous research projects have been created to lower energy usage at sintering plants; however, there has been no discernible decrease in CO_2 emissions. Researchers are focused on using biomass to reduce CO_2 emissions in the manufacture of iron and steel as a result of the ongoing release of massive amounts of CO_2 during the production of iron, which has long been a cause for worry. Biomass usage as a carbon-neutral material is an appealing approach for iron manufacture to minimize CO_2 emissions in order to address the environmental issues related to the iron and steel sectors [124]. To quantitatively assess the potential of biomass-assisted ironmaking technology to reduce CO_2 emissions, the calculation formula for energy savings and emission reduction was developed. For every ton of iron smelted, a blast furnace should burn around 500 kg of fuel and emit roughly 1.49 t of carbon dioxide. Approx. 3.67 kg of CO_2 may be reduced for every kilogram of carbon usage that is lowered. According to the calculations, the CO_2 emissions of the current blast furnace ironmaking process may be decreased by >40% if the blast furnace runs efficiently and the biomass is fully utilized in the pre-iron processes including sintering, pelletizing, coking, and injection [14]. Ng et al. [125] analyzed the effects of substituting solid biocarbon generated by torrefaction, pyrolysis (up to 900 °C), and hydrothermal treatment for coal injection. A conceptual research study using heat and mass balances together with modeling for thermodynamic equilibrium was used for further examination. They came to the conclusion that this might reduce greenhouse gas emissions by up to 20%; nevertheless, the value of using biocarbon would then be greatly influenced by its carbon-to-oxygen ratio. According to certain case studies presented in report [126], using biofuels exclusively in the place of fossil fuels can reduce steelmaking's emissions of greenhouse gas even by 25%. Other studies in the same report have estimated that using carbon-neutral biomass might lower net CO_2 emissions over the typical BF-BOF pathway by up to 58%.

In addition to being CO_2 neutral, biomass material is also probably lower in S, Cl, N, and other heavy metals, which are detrimental to the environment, human health, and metal quality [5]. The high sulfate content in coal causes SO_x emissions when it is burned. When SO_x is released into the atmosphere, it combines with water to produce acid rain, which has an adverse effect on the environment. As opposed to coal, biomass has a 10 times lower sulfur concentration. As a result, the environment is significantly cleaner. Nonetheless, the NO_x results are the same for both coal and biofuels [26].

According to the results of mathematical modeling developed by de Castro et al. [96], adding 150 kg/tHM of pulverized coal to 100 kg/tHM of charcoal will increase the efficiency of the blast furnace by about 25%, while optimizing oxygen enrichment. Another major benefit discovered by studies published to date is that biomass has a greater hydrogen concentration, which may ignite the sintering process more evenly and effectively at a lower ignition temperature.

3.3. The Challenges and Future Prospects in the Application of Lignocellulosic Biomass in the Steel and Iron Industry

In theory, metal-processing facilities might use biomass as bio-based fuel for a variety of uses. The advantages of such a method, however, are often limited owing to its low heating value and might be offset, for instance, by the high expenses associated with preprocessing and transportation. Biomass must first be transformed into charcoals (chars) through pyrolysis or torrefaction processes since raw biomass is unsuitable for usage in the production of iron and steel [67]. On the other hand, the negative impact of biomass on the thermoplastic qualities of metallurgical coke limits the possibility of replacing coke (or even partially). A solution has not been found yet for keeping the coke bed mechanically strong in vertical shaft furnaces. This was not possible even with the introduction of small amounts of biomass, like sawdust or charcoal [120]. Even with minor (5 wt%) additions of biomaterials to the coking mix, it is predicted that the wide devolatilization range will eventually result in increased mass loss and decreased coke thermoplasticity and mechanical strength. A striking finding from other sources is that the same thermal study of Kraft lignin from softwood (pine or spruce) reveals minimal to no secondary devolatilization ranges [127]. Since pulverized coal injection (PCI) can already contain some amounts of nut coke or charcoal, replacing it represents the technically easier choice [2]. Similar environmental advantages to using bio-coke will result from the injection of charcoal, which will take the place of tuyere oil or coal injection. Additionally, it has been said that the use of biochar will boost reactivity and aid in reducing slag and ash production during smelting processes [128].

In the iron and steel sector, there are numerous distinct pyrometallurgical processes. As a result, the process itself and the function of the carbon material in the process determine the requirements for the qualities of carbon material. The BF processes have the strictest criteria for the characteristics of the carbon material because metallurgical coke plays a crucial role in maintaining the process' permeability and carburizing the iron. It is also being utilized as a reductant and a source of heat. As a result, severe criteria are placed on the qualities of carbon material, including mechanical strength, reactivity, and density. Other pyrometallurgical processes may have less stringent criteria, but they all require materials to have the same crucial qualities, such mechanical strength, reactivity, and apparent density [129]. When pyrometallurgical operations use biocarbon instead of carbon derived from fossil fuels, there are several difficulties. The enormous surface area and very porous structure of biocarbon cause an unfavorable increase in CO_2 gasification reactivity [130]. However, according to Koskela et al. [131], pyrolysis temperature as well as briquetting, i.e., agglomeration, can change the gasification reactivity of biocarbon. The structural features of biocarbon are changed by high pyrolysis temperatures and briquetting which result in a denser and smaller surface area. This is connected to the selection of the raw material and its lignin content for the production of biocarbon. This is because lignin possesses an adhesive quality, which enhances the binding of the particles during briquetting. According to research performed by Wiklund et al. [132] as well as Helle et al. [133] and Babich et al. [74], the pyrolysis temperature also has a significant impact on the biomass composition, calorific value, and output yield. In these works, with the example of Norway spruce, the content of hydrogen, oxygen, carbon, as well as the calorific value and yield depending on the pyrolysis temperature, were analyzed. However, in the temperature range up to 500 °C, the observed changes in these parameters were the greatest, and at temperatures between 600 and 800 °C, both the composition and the calorific value differed slightly.

Biomass addition to the coal blend used to make coke has recently been the subject of intense research. Operating a blast furnace (BF) requires the use of carbon-bearing materials, and the standards are stringent. CRI and CSR are two of the most crucial factors in determining whether to use metallurgical coke in a BF. The industrial quality standards for coke are a CRI—coke reactivity index—under 30% and a CSR—coke strength after reactivity—above 55%, while in European countries, the CRI and CSR standards in BFs are 23% and 65%, respectively [128]. According to Safarian et al. [134], the maximum quantity of biochar that may be blended with coal in order to make bio-coke of a high enough quality greatly depends on three indications of fluidity as well as CSR and CRI. The findings demonstrated by them showed that adding charcoal often causes the fluidity of the coal–biochar mixture to diminish. The CRI, CSR, and fluidity indices of the coke decrease when biochar is added to coking coal, and biochar has a detrimental impact on the quality of the output coke. It was discovered that in order to prevent negative effects on the quality of the resultant coke, biochar must be added continuously at a rate of between 2 and 10% during the coke-making process. Adding 2 to 10% biochar to the coal mix decreases CO_2 emissions in the steel sector by 1–5%, which is valued at 0.02–0.11 tons of CO_2/ton of crude steel. The CSR and CRI of the coke also fall, although fluidity marginally improves as a result of lowering the particle size of the biochar. A range of 2–4 mm was determined to be the ideal particle size for biochar [135].

In turn, the results of research performed by Yustanti et al. [136] showed that two analyzed coking blends of coke with biochar from coconut shells as well as rice husks generated comparable tendencies. The coke quality blends degraded as the biochar proportion rise, i.e., from 0 to 25 wt%, as shown by the CSR index decreasing and the CRI index increasing in the case of both biomass species. For the analyzed biochar proportion of blends of coke with rice husks, the CSR index was from 62.7% to 24.5% and in the case of coconut shells, was from 62.7% to 42.6%. In turn, the CRI index was rising in case of blend of coke with rice husks from 21.3% to 47.3% and in case of coconut shells from 21.3% to 32.9%. Thus, in order to maintain good-quality coke, the CRI index should be, if possible, the lowest, while the CSR index should be the highest.

An interesting study was presented by Gul et al. [137], who proposed using cutting-edge techniques to make biocarbon on the route of pelletization of charcoal with pyrolysis oils and then reheating it at conditions of high temperatures in order to generate materials characterized by sufficient hardness, decreased porosity, and appropriate reactivity. After such pretreatment, biocarbon can meet the standards typically required for metallurgical coke. A technological, economic, and environmental study of the anticipated end application of biocarbon in the steel and silicon industries was provided. Based on their research, the use of biocarbon pellet in the steel industry will undoubtedly have some positive environmental effects. The cost of the feedstock, shipping expenses, cost of the transformation, and expenditures of the pyrolysis plant are just a few of the numerous variables that will determine the economic viability. According to Hakala et al. [67], the cost of producing one tonne of biochar might be 252 euros, which is the lowest calculated price that can obtained. The price of the EU Emission Trade System, especially EUA entitles businesses to release GHGs with a global warming potential equal to one tonne of CO_2 equivalent, and the price of coke will both have an impact on the eventual profitability of the biocarbon use in the steel sector. According to Gul et al. [137], it is challenging to have an economic convenience when the EUA costs 25 EUR /tCO_2, unless coke costs more than 200 EUR /t. In the global market, it is quite challenging to achieve this value. The material's quality must, thus, be improved in order to achieve the same qualities as coke, even if some economic factors still need to be optimized, primarily focused on technology and raw material cost reduction. As a result, the created biocarbon pellet has to be examined in accordance with all the usual standards used to describe coke, including the ISO 18894:2018.

According to Fan et al. [126], the actual use of biomass is severely constrained, and there are still considerable technological barriers preventing its full replacement of fossil fuels in the BF-BOF process, including, first of all, the cost. Currently, the price of bio-charcoal ranges from USD295 to USD525 per ton, while the price of coke (coal that has undergone the coking process) is around USD200 per ton. Purely economically, biomass cannot yet compete with coal. Secondly, another barrier is the physical characteristics. Biocharcoal differs from coal or coke in terms of physical characteristics (such as mechanical strength, etc.), and manufacturing performance criteria may not be guaranteed. The qualities of bio-coke that is used to directly replace coke in BF must be comparable to those of regular coal. Furthermore, Gaurav Jha et al. [26] listed the qualities being necessary for any fuel used in metallurgical operations that should be primarily profitable from the perspectives of availability, storage, acceptability, etc. The biochar ought to be characterized by: high heating value and energy density; low ash and moisture content; low levels of pollution and impurities; easy and abundant availability; reasonable price; ease to transport; flame resistance in an open space. Thirdly, another barrier is the supply chain quality. The worldwide supply networks are immature and sometimes poorly managed, and biomass resources are allocated unevenly. Brazil is the world's top producer of biochar, followed by China, India, and the United States. Bio-charcoal might legitimately service a small portion of the steel industry in such areas. Contrarily, the EU now imports 70% of its bio-charcoal from Africa, which has increased worries about deforestation, biodiversity loss, and eco-colonialism. Similar worries are raised by the absence of indigenous biomass supplies in Japan and Korea [126].

- The use of biomass in the iron and steel sector is currently rather restricted, and it faces stiff competition from traditional fossil fuels. Technical and financial issues that call for cooperation between the steel industry and the bioenergy sector are among the difficulties associated with using biomass in the steel industry. Although a significant effort has been made up to this point, there is still long way to industrial application of biomass in iron and steel sector on the wide scale. A peculiarity of Brazil in comparison to other countries consists of the fact that its main energy sources for steel production are coal, electricity, and charcoal obtained from biomass. The example of Brazil, which is one of the biggest steel producers in the world, shows that application of lignocellulosic biomass in steel sector can be possible not only on a pilot scale but also on a wider, industrial scale [138,139].
- According to a report presented by ArcelorMittal [140] in 2018, the company started a EUR 40 million Torero demonstration project in Belgium (Ghent) using 120,000 tonnes of waste wood to create bio-coal that may be used in place of fossil fuels to reduce iron ore. The technique may be able to handle a range of waste streams (such as bio-based and plastic waste) produced by society.

4. Summary and Conclusions

Among all industrial sectors, the iron and steel industry is the largest energy user. Coal, liquid and gaseous fuels, and electricity are the primary energy sources in this energy-intensive sector of the economy. The iron and steel industry places a high priority on energy because of the high energy intensity and the significant contribution of fossil fuels. Additionally, the steel and iron industries are subject to rivalry on a global scale, and producing steel using less energy may provide them an edge. The usage of fossil carbon is presently a major component of the metal manufacturing and processing business. Both the smelting reduction required to produce pure metal from ores and the energy supply for the subsequent processing steps, where heavy mineral oils are typically utilized, depend on coal and coke. With 4–7% of worldwide emissions and a comparable range in European emissions, the production of iron and steel is among the top industrial carbon dioxide emitters. This paper examined the idea, scientific theories, and research in the field of biomass application in metallurgy as a replacement of coal.

Clearly, there is still a long way to go before biomass materials are widely used in metallurgical sectors. First, biomass materials must attain properties that are best suited for their future uses, such as the sintering of iron ore and the production of iron in blast furnaces. The cost and accessibility of biomass materials must also be taken into account, in addition to their appropriateness for metallurgical applications in terms of quality. Two significant barriers to the adoption of biomass materials in metallurgical industries are their cost and availability. There is an urgent need for more study on the production chain and availability of biomass resources for metallurgical purposes. Also, actions in the development and management of the use of biomass in a sustainable manner and to enhance a production technology with high efficiency, low cost, and lower environmental impact should be taken.

Author Contributions: Conceptualization, A.B.-P., M.Z., A.S., M.S. (Magdalena Skrzyniarz), J.R., and M.S. (Marcin Sajdak); writing—original draft preparation, A.B.-P., M.S. (Magdalena Skrzyniarz), and M.Z.; writing—review and editing, A.S., M.S. (Magdalena Skrzyniarz), A.B.-P., and M.Z.; supervision, M.S. (Marcin Sajdak) and J.R.; project administration, A.S., A.B.-P., and M.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data are contained within the article.

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

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