Review

Potential and Environmental Benefits of Biochar Utilization for Coal/Coke Substitution in the Steel Industry

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Abstract: The metallurgical sector is one of the most emission- and energy-intensive industries. The possibility of using fossil carbon substitutes has been investigated to reduce the environmental impact of the steelmaking sector. Among others, biochar emerged as a promising fossil coal/coke substitute. We conducted a literature review on biochar use in the metallurgical sector and its potential environmental benefits. The possibility for biochar as a coal/coke substitute is influenced by the source of biochar production and the process within which it can be used. In general, it has been observed that substitution of biochar ranging from a minimum of 5% to a maximum of 50% (mostly around 20–25%) is possible without affecting, or in some cases improving, the process, in coke making, iron sintering, blast furnaces and electric furnaces application. In some studies, the potential CO₂ reduction due to biochar use was estimated, ranging from 5% to about 50%. Despite there still being an area of further investigation, biochar appeared as a promising resource with a variety of uses in the metallurgical sector, contributing to the lowering of the environmental impact of the sector.

Keywords: biochar; biomass; circular economy; coke; decarbonization; environmental impact; furnace; steelmaking

1. Introduction

Globally, the steelmaking industry is considered one of the highest energy-consuming and emission-productive industries [1]. An estimated 20% of the energy used worldwide is accounted for by steelmaking, with coal and coke providing most of the energy [2]. The International Energy Agency statistics indicate that the ferrous metallurgical production accounts for almost 23% of all industrial CO₂ emissions worldwide [3]. Moreover, carbon emissions from the iron and steel manufacturers accounted for about 2600 million tons in 2019 and it was estimated to increase to 2700 million tons by 2050 if no sustainable development scenario would be used [3]. Currently, approximately 75% of the world’s steel is manufactured using the blast furnace—basic oxygen furnace (BF-BOF) processes [1]. Coke making, sintering, and blast furnace processes contribute together almost 90% of the total amount of CO₂ emissions in the iron and steel industry [3]. The main challenges for the sector are the reduction of carbon emissions and the achievement of sustainable production. For each step of the steelmaking process, a unique decarbonization strategy is needed when switching to low-carbon manufacturing processes [3]. Among strategies supporting the achievement of these objectives is raising in importance the use of an environmentally friendly and effective fossil coal/coke substitute [4]. A promising substitute for coal and coke in the metallurgical industry is biochar. Biochar, an organic substance rich in carbon, can be produced through the pyrolysis process, a thermal breakdown in the absence of oxygen converting the biomass source (i.e., agricultural residues, wood chips, organic waste) into a stable form of carbon; the resulting biochar is characterized by a permeable structure, high carbon content, and ability to retain water and nutrients [5]. Also,
torrefaction technology and hydrothermal carbonization offer favorable low-temperature biochar production methods.

Recent years indicate a significant rise in interest in biochar driven by its potential as a sustainable solution for various environmental and agricultural applications, such as carbon sequestration, soil improvement, and renewable energy production [6]. Biochar is considered a promising candidate to replace fossil fuels partially or completely in various iron and steelmaking processes, including coke production, iron ore sintering, blast furnace injection, and electric arc furnaces (EAF), exemplified by the compatibility of its properties, as well as its lowered environmental impact. Also, the application of biochar along with other secondary carbon biocarriers, i.e., biomass residues, torrefied biomass, etc., in metallurgical activities, has been reviewed by Kieush et al., (2022) [6] focusing on torrefied biomass. Torrefaction or mild pyrolysis refers to the thermal treatment of biomass under an inert atmosphere process at lower temperatures (200–300 °C) than the conventional form of pyrolysis (350–1100 °C) that enhances biomass characteristics without changing the high molecular content and preserving a higher yield of solid material usable as a carbon substitute [7]. Biochar, as a result of pyrolysis or gasification at 350–110 °C, is a byproduct of processes aimed mainly at energy production and the residual char is therefore regarded as a byproduct or waste material [8]. While the quality of biochar is lower than torrefied biomass, it has advantages such as the lower price and additional environmental benefits by increasing circularity. Hence, biochar can become a resource to be shared in initiatives such as industrial symbiosis among energy production and metallurgical sectors. Therefore, a detailed review of the potential applications, recommended levels of coal/coke substitution, and the effect of biochar origin (source) are crucial for forming a match between the available byproduct and the potential applications in metallurgical processes.

In this context, this paper aims to provide a recent overview of the potential of biochar use as a substitute for fossil coal in the steel industry, with focus on BF and EAF applications, and its contribution to the reduction of CO₂ emissions. By consolidating the current knowledge on biochar use in the metal industry, this paper seeks to contribute to the ongoing discourse on sustainable solutions for climate change mitigation in the metallurgical sector.

2. Materials and Methods

We conducted a literature review on the Scopus database. First, manuscripts related to the research topic were identified by using the following keywords combination: “Biochar” and “Coke”; “Biochar” and “Coal” and “Industry”; “Biochar” and “Steelmaking”. The manuscripts that resulted from the search were screened by reading the title and abstract to assess their relevance to the use of biochar as a substitute for fossil coal in the steel and iron industries. The full texts of the selected manuscripts were examined. Manuscripts relevant to the following criteria were included in the literature review: the most recent starting from the year 2024; describe the use of biochar in metallurgical activities, and specifically in the iron and steel industry, in its various processes; describe the sources of biochar and its performance in terms of efficiency and quality in replacing coal completely or partially; cover the contribution of biochar to CO₂ reduction and energy efficiency according to its different sources.

The results of the biochar utilization as a fossil coal/coke substitute in the steel industry, its sources and characteristics, and the environmental benefits of its use were then presented and discussed.

3. Results

3.1. Overview of Biochar Utilizations as a Coal/Coke Substitute in the Steelmaking Industry

The BF/BOF and the EAF are currently the two main methods used to produce iron and steel in the steelmaking industry. Coal is employed in steel manufacturing at different stages, encompassing the carbon reduction phase, in which iron oxide reduction processes use it as a carbon source. The main applications of biochar in the iron and
steel industry include coke making to produce bio-coke; sintering to produce bio-sinter; pelletizing/briquetting to produce bio-briquettes; partial replacement of coke or pulverized coal (PC) in the blast furnace; and bio-carburization of steel in the ladle furnace [2].

Kieush et al., (2022) [6] investigated the utilization of torrefied biomass—secondary carbon bio-carrier—as a substitute for coal and coke in the production of iron and steel-making. The most promising applications of secondary carbon bio-carriers include the process of melting scrap in an electric arc furnace (scrap/EAF); direct reduced iron/electric arc furnace (DRI/EAF) includes making carbon composite agglomerates (CCAs), smelting reduction/basic oxygen furnace (SR/BOF), and submerged arc furnace (SAF). The most appealing method to enhance the characteristics of torrefied biomass in this regard is to be torrefied at 200–300 °C [9], which is also known as a moderate pyrolysis process. After pyrolysis, torrefied biomass has less ash than biochar produced by pyrolysis, and can retain 90% of its energy [10].

The main processes and routes of biochar substitution in metallurgical activities in the iron and steelmaking industry can be summarized as follows (Figure 1):

- **BF/BOF route**: biochar can be used in coke making and iron ore sintering.
- **Scrap/EAF route**: biochar can be used to produce bio-coke, which can serve as a replacement for coke and coal in the scrap/EAF route.
- **DRI/EAF route**: considers using CCAs obtained using torrefied biomass in the DRI/EAF route. In the DRI/EAF route, it is feasible to utilize bio-coke as a carbon source up to 100% of the time, even while adding a significant quantity of torrefied biomass (up to 50%) into the coal blend. [7]. In the EAF process, carbon, in the form of coke or anthracite, can be used for charge, injection, or as a recarburizer [9].
- **SR/BOF route**: this process uses non-coking coal as a fuel source, with specific requirements for fixed carbon and volatile matter content. It includes the COREX process, which is a method used to produce hot metal from lumpy-iron carriers, primarily pellets, sinter, and lump ore. The most suitable conventional carbon source for the COREX process is non-coking coal (fixed carbon content 55–70 wt.%, ash content < 12 wt.%) [7].

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**Figure 1.** Different processes and routes of biochar substitution in metallurgical activities of the iron and steelmaking industry.

3.1.1. Biochar Substitution in Blast Furnace Technology

BF is currently the most common process for producing iron for steelmaking. The technique works on the premise of converting iron oxides to iron-utilizing carbon-based reducing agents. The use of carbon-bearing materials is required to run a BF, and the standards are stringent. The coke reactivity index (CRI) and the coke strength after reaction...
(CSR) are two of the most significant metrics to consider while employing metallurgical coke in a BF [10].

In a BF, biochar can be injected from the bottom (Pulverized Coal Injection, PCI) or used from the top as coke. PCI is the most effective in reducing the use of coke in BF. It is assumed that PC has 75% of carbon, while coke, coke breeze, anthracite, and recarburizer have 85% carbon [11]. A biochar sample derived from wood residues (from combustion at 600–1000 °C) containing 85–87% of C has characteristics similar to coals used in BFs [12].

Blending coke with biomass or biochar was also a solution to create biocoke with ideal properties of BF standard. In a study by Yustanti et al., (2021) [13], coke was mixed with biochar in the following wt.% ratios, by 95:5, 85:15, and 75:25. Biocoke of a mixture of coke and coconut shell biochar (85:15 wt.%) achieved the optimal ratio and met the blast furnace standards for higher efficiency. Blending (80:20 wt.%) biomass with coke resulted in a 15% decrease in total greenhouse gas emissions (GHG) [13]. In BF technology, biochar has a high potential to completely replace PCI and partially replace the coke in large blast furnaces [3].

Since the properties of the coke mixture require the creation of sufficient load-bearing strength in order to maintain the permeability of the layer, the mixture can be achieved with a maximum of 20% substitution with biochar, reducing CO$_2$ emissions by 0.33 t CO$_2$/t [11].

Secondary carbon bio-carriers in a BF can be thought of as the usage of biocoke produced with the addition of torrefied biomass. Torrefied biomass or biocoke is another option to create sinter, which is then used in the BF. One method consists of the use of the bio-pulverized coal injection technology, where up to 50% of the coal is replaced with torrefied biomass, or all of the coal is replaced with a combination of torrefied biomass and torrefied biomass post-carbonization. [7].

Studies about fossil fuel replacement for injection in BF via PCI showed a possibility of fossil carbon replacement in the range of 10–20% using hydrochar derived from eucalyptus, apple bagasse, and out-of-use wood. Hydrochars with higher lignin content showed higher reactivity, resulting as more appropriate to be used for gasification applications [14]. Hydrochars were demonstrated as not suitable to fully replace fossil-based injectant in BF, whereas they can be mixed with anthracite in the range of 30–60% depending on their origin material [14]. McMahon et al., (2023) [15] used a model to assess the usability of biochar for injection via PCI in BF, obtaining interesting results to be confirmed in laboratory and pilot scale experiments. Modeling a 30% replacement by biochar derived from waste wood material from the building industry and hardwood, an increase of the As and Pb concentrations was observed in BF flue dust as a result of the biochar use, but without exceeding the limits of the guidelines for these metals. Cost savings in displaced PCI and potential CO$_2$ reductions were also associated with the use of biochar [15].

3.1.2. Biochar Substitution in Coke Making Processes

The use of biochar blended with coke enhances the coke quality and the coking chamber production capacity [1]. As a result, while creating a blend including carbonized biochar, it is critical to determine its suitable proportion in the blend, allowing for the generation of biocoke with appropriate industrial specifications [1]. In coke making processes, biochar can be blended with fossil coke to make biocoke. By carbonizing coking coals at elevated temperatures (1000–1100 °C) without air, metallurgical coke is created. Moreover, it has been stated that lumpy charcoal may be used in place of metallurgical coke up to 20% of the time [16].

In coke processes, the inclusion of biochar reduces the dilatation of the mix, which affects some parameters, including improved reactivity [17]. A higher dilatation value results in a coking mix with superior coke making capabilities and higher coke quality. Unlike raw biomass, biochar could be applied to the coking blends in greater quantities. However, when composing the mixture with a bio-carbon additive, technological coefficients, such as the characteristics of the obtained biochar, the biochar grains distribution, the share of
biochar in the coke blend, the level of homogenization of the blend with the additive, and the blend charging method in the coking chamber, should be considered [17].

Biochar can be added in the range of 2–10% to maintain the quality of biocoke production [3,18,19]. Some limitations in coke replacement by biochar have been evidenced in reaching high CSR and low CRI, resulting in a lower quality of the obtained coke or in limiting the percentage of the biochar addition [20]. Testing with hardwood-derived biochar showed that the replacement should be within 2% while the particle size also counted as a parameter of influence, to be maintained in the range of 2.4–3.4 mm, to avoid the degradation of CSR and CRI and fluidity index [20].

Wang et al., (2023) [21] tested a mix of powder materials from biochar from sawdust and residual coke breeze in the proportion of 2:8, which resulted in having appropriate characteristics to satisfy the standard for high-quality secondary metallurgical coke. The cracks and pores inside the formed coke product can be filled with a suitable amount of sawdust biochar powder, improving its internal structure and performance. A following study by Wang et al., (2024) [22] revealed the possibility of using a mix of powder material from residual coke breeze and biochar from bamboo (biochar to coke breeze 2:8) in the percentage of 4%. The main reason for biochar is to give a better pressure resistance and density to briquettes, while saving the residual coal coke.

Biocoke optimized using blending ratios of inferior grade coal and biochar obtained from coconut shell, groundnut shell, sawdust, and sugar cane bagasse (pyrolysis at 550 °C), with starch and molasses binders via carbonization, was created in different proportions and tested in the laboratory. The study of the characteristics of the blend showed a potential for replacement of fossil carbon sources up to 20–30% [23].

3.1.3. Biochar Substitution in Iron Ore Sintering Processes

In iron ore sintering processes, it was found that a substitution of coke breeze by biochar between 40% and 60% resulted in a high-quality sintering product and kept the product yield >80% [3]. These values depend on the biochar’s fixed carbon content and its size range. As an example, a biochar with a fixed carbon content >90% and a size in the range of 1–5 mm can be added to the sintering plant at a percentage up to 60%, to obtain a product similar and of the same quality as that obtained by the use of coke breeze [2].

Niesler et al., (2021) [17] studied biochar obtained from three different biomasses: sawmill sawdust, residual woodchips, and sunflower husks. Biomass pyrolysis and iron ore sintering with biochar were conducted at a pilot and a semi-industrial scale, respectively. Sinter made with biochar resulted in a product with superior strength and resistance to abrasion, with an enhanced quality of the finished product, producing fewer sulfur oxides, and slightly more carbon compounds. In the same study, the elemental carbon content of coke breeze (83.8 wt%) and of biochar from residue-pelletized sawdust (82 wt%) were similar; however, the parameter values for biochar from residual woodchips and sunflower husks were lower, reaching 75 wt% and 73 wt%, respectively [17]. Additionally, all biochar samples had higher volatile matter contents than average (9.7–25 wt%) compared to the coke breeze (1.58 wt%). Biochar produced from pelletized leftovers of sawdust and residual woodchips would make it the ideal source of carbon for iron ore sintering processes, given its physicochemical structure in terms of grain size and volatile matter concentration [17].

In another study conducted by Mousa et al., (2015) [24], the focus was on the effect of substituting biochar for coke breeze in different ratios ranging from 0–100% on the performance and quality of sintering, without modifications on the ratio of other additives, such as iron ore, limestone, water, and fine returned in sintering mixtures. Results showed that the vertical sintering speed was reduced as the rate of substitution of biochar by coke breeze increased, as biochar negatively affected the permeability of the beds, resulting in a lower cracking strength of biochar compared to coke breeze. This led to a decrease in the production yield, mainly due to the formation of low-strength sinter due to the higher percentage of returned fines [24].
In a following study [2], the optimal ratio for mixing biochar with coke breeze resulted in about 25%, as it can achieve the required level of sintering quality and thus achieve the required productivity. Gan et al., (2015) [25] stated that it was possible to reach an optimal alternative to biochar for the coke breeze with a replacement rate of 40%.

Other studies highlighted the limitations of using biochar in the sintering: the replacement of >40% of coke breeze with charcoal caused a reduction in the combustion efficiency, while tests on biochar obtained from sawdust, nutshell, and other waste charcoal showed a deterioration in sintering strength after 60% replacement [20].

An innovative divided fuel addition method combining coke and biochar was proposed to improve the fuel distribution in the iron ore sintering process, to optimize the replacement of fossil fuel by biochar in iron sintering BF processes. Two commercial biochars from commercial suppliers were tested, showing that the appropriate replacement proportion of biochar can be increased from 40% to 50% using the divided fuel addition method [26].

3.1.4. Biochar Substitution in the Electric Arc Furnace

The EAF is considered, after BF, as one of the most common steelmaking processes. Approximately 29% of crude steel produced worldwide in 2018 was manufactured in EAF [27]. The World Steel Association reports that 28% of global steel production is based on EAFs, and 42% of the Europe steel output [28]. Most of the carbon in EAFs is derived from electricity using a small amount of carbon-bearing material [29]. The use of fossil carbon during the scrap steel-melting process in EAFs accounts for approximately 60–70% of the direct GHG emissions from steelmaking [30]. It is possible to lessen the effect of steelmaking on the environment by employing renewable biochar in EAFs [30]. The EAF pathway is enhanced with a carbon-bearing substance to serve these functions: (a) charge carbon, to minimize oxidation of alloys and metals by adding chemical energy and creating a reducing atmosphere during melting; (b) increase energy efficiency and productivity, lower operating costs, and improve steel quality by using slag foaming technology; (c) to be used in the ladle furnace for carburizing purposes [31].

As a replacement for conventional fuels, Huang et al., (2019) [30] examined five carbon-bearing samples: biochar from wood biomass produced by slow pyrolysis at 900 °C, by fast pyrolysis of at 400 °C, metallurgical coke, semicoke, and technical graphite generated by 700 °C pyrolysis of waste tires. As compared to other carbon-based materials, the authors concluded that biochar did not interact well with slag [30].

Meier et al., (2017) [31] investigated the application of different carbon carriers in an EAF using a dynamic process simulation model, utilizing virgin ligneous biomass (palm kernel shells) and charcoal derived from pyrolysis and torrefaction. Findings showed that palm kernel shells behaved differently than anthracite, producing chemical energy with high volatile content earlier during heat [31]. The use of palm kernel shells is technically feasible in EAF processes and did not show negative results in long-term industrial uses. Echterhof et al., (2021) [9] gave an evaluation of the EAF steel production route’s use of alternate carbon sources. According to the assessment, alternative carbon sources are required in the EAF to create ecologically benign and carbon-neutral steel [9].

A study compared biochar from grape and pumpkin seeds to coals usually employed in EAF processes, observing that, for its characteristics, pumpkin seeds-derived biochar had the potential to replace charge carbon, and grape seeds-derived biochar to replace injection and charge carbon, instead of anthracite [32].

A pilot scale experiment compared the melting process of steel using coal to biochar from hydrothermal carbonization, and showed that the use of biochar decreased the duration of the melting process, without affecting the quality of the produced steel, even if a risk of an incomplete reaction was evidenced [33]. Pilot scale experiments by Cirilli et al., (2017) [34] confirmed the possibility of using biochar as a replacement for fossil fuel in EAF as charge material, without impacting the quality of the produced steel, with advantages in terms of emissions reduction, even if with higher costs when using commercial biochar.
Kieush et al., (2022) [6] studied the possibility of using a secondary carbon bio-carrier (biocoke) where the raw material is scrap: in EAF, biocoke can be used as a charge carbon and as injected carbon, as well as a carbonizer source in a ladle furnace. Additionally, CCAs derived from torrefied biomass can be used in the DRI/EAF route. Another interesting pathway for further investigation is the use of biocoke containing a significant quantity of torrefied biomass in the DRI/EAF route. Due to its features, the usage of torrefied biomass is essentially limited; however, biocoke can be used as a carbon source up to 100%, even when torrefied biomass is added at a high rate up to 50% of the coal blend. This is due to its ability to satisfy the process requirements for having a fixed carbon content of at least 85%, necessary for steel carburizing or for producing foamy slag, which increases the melting process energy efficiency. Furthermore, the utilization of biocoke produced with up to 50% torrefied biomass in the DRI/EAF route is also a viable option. According to the authors, these pathways demonstrate the potential for integrating biochar and carbon biocarriers in the DRI/EAF route for steel production [6].

Biochar was investigated as a substitute for fossil coal in the EAFs process [35] when it was synthesized by either biomass torrefaction, slow pyrolysis, or hydrothermal carbonization. A three-dimensional computational fluid dynamics was used to model the combustion process and electrode radiation inside an EAF, where the particle surface and gas-phase reactions were assumed to forecast the combustion process of injected biochar particles. Biochar was shown to be a suitable alternative for the coal/coke in the EAF processes of steelmaking with similar quality to that of coal or natural gas.

Laboratory-scale tests were conducted by Robinson et al., (2022) [28] using carbonaceous materials: synthetic graphite, anthracite charcoal, biochar derived from commercial wood chips from logging residues (BC1), and commercial biochar wood pellets from sawdust (BC2). Results showed that the properties of biochar such as low carbon crystallinity and high porosity, which were considered harmful factors, did not present challenges for the process when using biochar as a carburetor. According to this analysis, BC2 had a porosity almost 1.5 times higher than anthracite (30% and 20%, respectively). Compared to BC2 and anthracite, BC1 had a slower dissolution rate, which can be attributable to its higher ash concentration. It demonstrates that the dissolving kinetics of biochar BC2 were comparable to those of premium anthracite coal [28]. An industrial-scale experiment was then performed in a 50-ton EAF at the Höganäs Halmstad plant in Sweden, at different increasing temperatures, to assess the biochar impact on the steelmaking process [28]. The replacement of 33% of the standard anthracite carbon charge with biochar BC2 gave results comparable with those obtained under normal EAF operating conditions.

Coal/coke and other fossil carbon sources are used as foaming agents in EAF, to create foam slag that protects refractory materials from the heat intensity, increasing the energy efficiency, and the duration of the smelting cycle and the noise. Laboratory experiments with biochar derived from pine sawdust, hydrothermally treated, showed a higher foaming time (353 s) than that of fossil-derived foaming agent (219 s), and a better performance in terms of foaming stability and slag viscosity [36]. Another study [37] tested corn stalk biochar treated by pyrolysis, superheated steam, and hydrothermal carbonization, as foaming agents. Feasibility studies results evidenced that the hydrochar was suitable for injection into the steel and superheated steam-treated char was suitable to be directly injected in the slag. While tested chars showed the potential to replace coke in EAF as foaming agents, their surface morphology represents a critical aspect while the amount of volatile fraction in hydrochars can be beneficial. Biochar as injection carbon in the EAF steelmaking process was studied by Di Giovanni et al., (2023) [38] to evaluate the effect on slag foaming through a series of melting experiments. Compared to conventional fossil-derived materials, loose biochar pellets ranked as the least effective material tested, whilst bio-briquettes appeared as promising candidates for further testing. Another study demonstrated biocoke to be a suitable material to be used in EAF as a source of injection carbon, based on laboratory analysis comparing different carbon-bearing materials [39].
A mix of biochar with coke, supplemented with FeO, ranging from 15 wt.% to 40 wt.%, resulted in stable foaming [40].

Finally, an interesting study by Dall’Osto et al., (2023) [41] investigated the feasibility of using biochar as a source of renewable electricity, because the EAF steelmaking process is highly dependent on electricity and consequently a source of indirect emissions. The usability of a low-temperature molten hydroxide direct carbon fuel cell as an additional energy source for steel production by EAF was assessed, testing torrefied biochar and pelletized hydrochar. Although chars showed lower electrical performance than coke, they appeared suitable for electricity generation both in pellet and powder form, with torrefied biochar having superior performance than hydrochar when inserted as powder [41].

3.2. Characterization of Biochar under Different Carbon Sources and Production Processes

Generally, literature evidenced that the fixed carbon content, as well as calorific values, showed lower values in biochar than in coal and coke. However, biochar can count on higher volatile matter and impurities in the ash than those found in fossil-based carbon sources [17,19]. Also, biochar has a porous structure compared to coals, generally more densely packed [19].

A review by Safarian et al., 2023 [3] examined biochar as a potential alternative to fossil coke and coal. The authors investigated the main challenges affecting the steelmaking industry and the potential of using biochar to address these difficulties. It also focused on evaluating the replacement of coke with biochar from the metallurgical, technical, and environmental aspects, from feedstock utilization to steel production. The authors found physical and chemical characteristics of biochar derived from wood and wood biomass could represent a good alternative to fossil coal and coke with properties such as the content of fixed carbon >80% and the calorific value >27 MJ/kg. Biochar sourced from agricultural waste can also be considered as a useful alternative to coke and coal, as it has been shown that lignocellulose biomass contains high levels of carbon content, up to 39–57% [42].

A comparative study on conventional and non-conventional carbon sources (biochar and biocoke) for EAF applications determined biochar as the material with a lower fixed carbon value, with lower ash content and higher reactivity than biocoke [43]. Similar characteristics emerged in other studies [19,31,35,38].

A study investigated the characterization of biochar from two sources, rice husks and coconut shells, with molasses as a binding agent, varying the temperature, at 20 MPa for 4 h [13]. The compressive strength produced by rice husk biocoke at 150 °C resulted in about 2.09 MPa, and that by coconut shells resulted in 1.58 MPa at 100 °C, which made it more suitable to replace coke and coal in the steelmaking processes [13]. The biochar fixed carbon content of coconut shells ranged 60–70%, in agreement with other studies [2], while the biochar fixed carbon of rice husks ranged 38–40%. The calorific value of biochar from rice husks resulted in about half the value of biochar from coconut shells (9–13% and 28–30 MJ/kg, respectively) [13].

Biochar derived from cotton waste denim was found to show advantages in terms of pore structure distribution and small particles when compared with fossil-based carbons [44].

Processes for biochar production, such as pyrolysis, gasification, and hydrothermal carbonization, influence their properties and can support their optimization [3,42]. The pyrolysis process at low temperatures was shown to produce high yield biochar, and pyrolysis at high temperatures produced biochar with low yield, high C, and high heating value [45]. By comparison, wood residue biochar had higher heating value than rice residue biochar (21–24 MJ/kg and 17–19 MJ/kg, respectively,) and lower H/C and O/C atomic ratios (0.643–0.201 and 0.326–0.084, respectively) [45]. The wood residue biochar contains significantly more carbon than typical PCI (75% C). It also contains less ash and sulfur than what is required for BF, coke breeze, and recarburizers altogether. In comparison with wood residue biochar (600–1000 °C), there is weak prudence in the use of rice residue
biochar (400–1000 °C) due to its low persistence, lower heating value, and higher alkali and alkaline earth metal content, than the threshold for an appropriate solid fuel [45].

Hydrothermal carbonization was demonstrated to improve biochar properties when used as a foaming agent in EAF, with high temperature being the most influencing parameter, followed by the solid/liquid ratio [36]. Hydrothermal carbonization has also been shown to enhance biomass properties when applied to apple bagasse and out-of-use wood, increasing the fixed carbon content and the calorific value [14]. Gasification requires higher temperatures than pyrolysis or hydrothermal carbonization, but the highest energy requirements can be met by combining them in steelmaking processes using heat recovery strategies [42].

3.3. Biochar CO$_2$ Reduction Contribution in the Steelmaking Industry

It was estimated that biochar can contribute to reducing CO$_2$ emissions by up to 80% under optimal conditions when derived from certain sources that make its properties similar to those of coke and coal [1,42]. Its ability to reduce CO$_2$ may depend on the steelmaking applications or the percentage of partial or full substitution for a specific source and process. Biochar use instead of fossil carbon-based materials can reduce CO$_2$ emission by about 19–28% in BF applications [3,10,42,45–47]. For the BF/BOF route, a 20% biomass substitution by biochar from rice husk or coconut shells could reduce GHG emissions by about 15% [13]. Torrefied biomass in BF application supports the decreasing of CO$_2$ emissions by about 15% [6]. The replacement of coke breeze by biochar in the sintering process was estimated to contribute to the decrease of the net CO$_2$ emissions by 5–15% [3,24,25]. CO$_2$ emissions reduction between 18% and 40% was reported when injecting pulverized biochar particles in a BF [19]. Replacing fossil fuels with renewable fuels sourced from agricultural waste biomass was estimated to reduce CO$_2$ emissions by 20–80% [42].

Models developed in different studies predicted the emission decrease due to biochar use in steelmaking. Meng et al., (2024) [48] estimated an emission reduction percentage of about 68% using wood- or straw-derived biochar, hypothesizing a replacement of 50% in sintering and BF, and 5% in coke making. The same study modeled the reduction of GHG emissions due to complete wood- or straw-derived biochar replacement in the EAF route, expected to be about 40% [48]. A review reported a reduction of about 6–57% in coke making and sintering, respectively [10]. Other studies provided lower emission reduction yields (5–15%) for iron sintering and EAF processes depending on the percentage of biochar substitution and biochar sources such as residual biomass, sawdust, and woodchips [3,17,24]. An LCA study compared emissions from different scenarios that included the partial replacement of fossil-derived materials by biochar [29]. It resulted in a reduction in the GHG footprint in the range 31–57% in the integrated steelmaking route, 5–11% in small scale EAF, and 16–80% in direct smelting, not considering byproduct and energy credits [29].

Wei et al., (2024) [36] investigated carbon neutrality opportunities in EAF foaming, evidencing that the use of hydrothermally treated char compared to conventional foaming agents did not show differences in CO$_2$ emissions while having the advantage of deriving from a net CO$_2$-neutral process.

Tables 1 and 2 summarize the main results of this paper, highlighting for the main routes analyzed (BF and EAF) the possibility of coal/coke replacement by biochar, relevant findings, and the estimated contribution to CO$_2$ reduction.
### Table 1. Main results from the review for BF/BOF route: source of biochar, processes, and possibilities for coal/coke replacement, efficiency, estimated contribution to CO₂ reduction.

<table>
<thead>
<tr>
<th>Steel Process</th>
<th>Biochar Source</th>
<th>Substitution to Fossil Carbon Source</th>
<th>CO₂ Reduction Contribution</th>
<th>Production Efficiency</th>
<th>Reference Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BF applications</strong></td>
<td>Biomass Ash wood</td>
<td>Biochar can replace up to 25% of coke in blast furnaces.</td>
<td>-</td>
<td>Can replace up to 20% of the energy from coke.</td>
<td>[1] R</td>
</tr>
<tr>
<td>Rice husks</td>
<td>An 85:15 wt.%, blend of coconut-shell charcoal and coking coal yields biocoke suitable for steelmaking, meeting blast-furnace criteria for CSR and CRI.</td>
<td>20% biomass substitution in steelmaking blast furnaces reduces CO₂ emissions by 300 kg/HIM (15% decrease in total GHG emissions).</td>
<td>-</td>
<td>[13] R</td>
<td></td>
</tr>
<tr>
<td>Coconut shells</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood residues</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td>[45] R</td>
</tr>
<tr>
<td><strong>Ironmaking BF</strong></td>
<td>Torrefied biomass</td>
<td>Torrefied biomass could replace PCI coal by 23%.</td>
<td>Modeling complete replacement with biochar, reduction of on-site emissions by 28%. PCI potential for net emissions reduction: 0.4-0.6 t-CO₂/t crude steel (19–25%) emission reduction: 0.40 Mt CO₂/y for torrefied wood.</td>
<td>-</td>
<td>[47] R</td>
</tr>
<tr>
<td><strong>BF-BOF route (overall)</strong></td>
<td>Wood-based biochar, straw-based biochar</td>
<td>Settings: coking 6%, sintering 50%, pelletizing 50%, BF 75/50%.</td>
<td>68.57-70.75% reduction of CO₂ emissions. An estimate based on MFA study using literature data.</td>
<td>MFA study</td>
<td>[46] M</td>
</tr>
<tr>
<td><strong>BF-BOF route (overall)</strong></td>
<td>Agricultural wastes</td>
<td>-</td>
<td>Can reduce CO₂ emissions by 20–80%.</td>
<td>-</td>
<td>[42] R</td>
</tr>
<tr>
<td>Coke making</td>
<td>Hardwood</td>
<td>2%</td>
<td>CRI, CSR, and fluidity index deterioration.</td>
<td></td>
<td>[20] R</td>
</tr>
<tr>
<td>Sintering</td>
<td>Charcoal nutshell, sawdust, and other biomasses</td>
<td>0%</td>
<td>Flame front speed increase.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Iron Sintering</strong></td>
<td>Sawmill residues, wood, lignocellulosic biomass, sewage sludge, coal, biomass blends</td>
<td>-</td>
<td>The use of different processes leads CO₂ emission reductions ranging from 6.7% to 57%.</td>
<td>-</td>
<td>[10] R</td>
</tr>
<tr>
<td>Coke making</td>
<td>Sintering: a replacement for up to 100% of coke breeze in the sinter mix.</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coke making</td>
<td>Coke making: a potential replacement for coal in producing coke.</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Coke making</strong></td>
<td>Addition ratio of biomass to coking coal blends should not exceed 5 wt% to maintain coke strength.</td>
<td>-</td>
<td>Biomass substitution in the sintering process can decrease the yield, tumbler strength, and utilization factor of sintering ore.</td>
<td>-</td>
<td>[18] R</td>
</tr>
<tr>
<td>Coke making</td>
<td>Chestnut and/or pine sawdust char</td>
<td>1–10 wt%</td>
<td>Increasing reactivity, CRI increases and CSR decreases by augmenting the percentage of biochar replacement.</td>
<td></td>
<td>[19] R</td>
</tr>
<tr>
<td>Coke making</td>
<td>-</td>
<td>-</td>
<td></td>
<td>Biochar addition in coke making enhances coke quality.</td>
<td>[1] L</td>
</tr>
<tr>
<td>Coke making and BF</td>
<td>A mix of powder material from residual coke breeze and biochar from bamboo</td>
<td>4% can be replaced by briquettes of tar+ residual breeze+ biochar (biochar to coke breeze 2.8).</td>
<td>-</td>
<td>The main reason for the use of biochar is to give better pressure resistance and density to briquettes.</td>
<td>[22] P</td>
</tr>
<tr>
<td>Coke making and BF</td>
<td>Biochars of coconut shell, groundnut shell, sawdust, sugarcane bagasse</td>
<td>20–30%</td>
<td>CO₂ reduction is the second target of the study.</td>
<td>Biochar was optimized using blending ratios of inferior grade coal and biochars (pyrolysis at 550 °C), with starch and molasses binders via carbonization.</td>
<td>[23] L</td>
</tr>
</tbody>
</table>
Table 1. Cont.

<table>
<thead>
<tr>
<th>Steel Process</th>
<th>Biochar Source</th>
<th>Substitution to Fossil Carbon Source</th>
<th>CO₂ Reduction Contribution</th>
<th>Production Efficiency</th>
<th>Reference Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coke making and BF</td>
<td>A mix of powder material from residual coke breeze and biochar from sawdust</td>
<td>Biocoke made from coke breeze and sawdust biochar (biochar to coke breeze 2.8)</td>
<td>-</td>
<td>The selected mix can satisfy characterization according to the Chinese standard for high-quality secondary metallurgical coke. Improved internal structure and performance by filling internal cracks and pores with a suitable amount of sawdust biochar powder.</td>
<td>[21] L</td>
</tr>
<tr>
<td>Injection in BF via PCI</td>
<td>Eucalyptus, apple bagasse, out-of-use wood, treated via hydrothermal process (to produce hydrochar)</td>
<td>10 and 20%</td>
<td>-</td>
<td>Hydrochars with higher lignin content showed higher reactivity; more appropriate to be used for gasification applications.</td>
<td>[14] L</td>
</tr>
<tr>
<td>Iron ore sintering</td>
<td>Waste wood material from the building industry; hardwood</td>
<td>30%</td>
<td>-</td>
<td>In model results, higher As and Pb concentrations were observed in the flue dust, without exceeding the limits.</td>
<td>[15] M</td>
</tr>
<tr>
<td>Iron ore sintering</td>
<td>Residual biomass of pelletized sawmill, sawdust (SDP), woodchips (WdC), sunflower husks (SH)</td>
<td>Biochar substitution should be below 30 wt% for residual biomass, except for sunflower husk biochar which should be below 10 wt%.</td>
<td>5–15%</td>
<td>28% SDP biochar increased production efficiency by 6%. 12% WdC biochar increased production efficiency by 2.5%. SH led to decrease in production efficiency by 9%.</td>
<td>[17] P</td>
</tr>
<tr>
<td>Iron ore sintering</td>
<td>Coke breeze</td>
<td>With 100% coke breeze, 25% biochar, 50% biochar, 75% biochar, and 100% biochar.</td>
<td>5–15%</td>
<td>Replacement of 25% coke breeze with biochar increased the production quality.</td>
<td>[2] R</td>
</tr>
<tr>
<td>Iron ore sintering</td>
<td>Cotton waste denim</td>
<td></td>
<td>-</td>
<td>Biochar has significant advantages in morphology (reasonable pore structure distribution and small particles).</td>
<td>[44] L</td>
</tr>
<tr>
<td>Iron ore sintering</td>
<td>Two commercial biochars from an industrial supplier</td>
<td>The proportion of biochar replacement can increase from 40% to 50% by dividing the fuel addition.</td>
<td>-</td>
<td>The proposed method of divided fuel addition using coke and biochar can optimize the distribution of the fuel in iron ore sintering</td>
<td>[26] P</td>
</tr>
<tr>
<td>BF/BOF (overall)</td>
<td>Sawdust, lignin, corn straw, walnut shell, wood-based biochar</td>
<td>In large blast furnaces, the maximum substitution percentage of biochar is around 20%.</td>
<td>In blast furnaces, net CO₂ emissions are reduced by 19% to 25%. In sintering, net CO₂ emissions estimated to decrease by around 5% to 15%.</td>
<td>Torrefied biomass in BF reduces CO₂-equivalent emissions by 14.7%. In BF, pulverized biomass char injection and charcoal lumps loaded at the top of the furnace achieve 14–15% CO₂-equivalent reductions, respectively.</td>
<td>[3] R</td>
</tr>
</tbody>
</table>
Table 2. Main results from the review for EAF route: source of biochar, processes, and possibilities for coal/coke replacement, efficiency, estimated contribution to CO$_2$ reduction.

<table>
<thead>
<tr>
<th>Steel Process</th>
<th>Biochar Source</th>
<th>Substitution to Fossil Carbon Sources</th>
<th>CO$_2$ Reduction Contribution</th>
<th>Production Efficiency</th>
<th>Reference Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAF route (overall)</td>
<td>Wood-based biochar; straw-based biochar</td>
<td>100%</td>
<td>41.06–42.67% reduction of CO$_2$ emissions</td>
<td>MFA study</td>
<td>[48] M</td>
</tr>
<tr>
<td>EAF route (overall)</td>
<td>Woody biomass BC1: logging residues wood chips BC2: sawdust wood pellets</td>
<td>33% biochar BC2 substitution</td>
<td>-</td>
<td>No deviation from normal conditions.</td>
<td>[28] F</td>
</tr>
<tr>
<td>Foaming</td>
<td>Pine sawdust hydrothermally treated</td>
<td>-</td>
<td>-</td>
<td>Biochar showed a foaming time of 353 s vs. fossil-derived foaming agent (219 s), under optimized conditions.</td>
<td>[36] L</td>
</tr>
<tr>
<td>Foaming</td>
<td>Corn stalk biochar treated via (1) pyrolysis in Nitrogen, (2) superheated steam, and (3) hydrothermal corn stalk biochar (Hydrochar)</td>
<td>Feasibility study</td>
<td>-</td>
<td>Hydrochars and superheated steam-treated char can replace coke as foaming agent (hydrochar suitable for injection, superheated steam char suitable to be directly injected in the slag).</td>
<td>[37] L</td>
</tr>
<tr>
<td>Foaming</td>
<td>Biochar from woody biomass (slow pyrolysis at 900°C), biochar from woody biomass (fast pyrolysis at 400°C)</td>
<td>-</td>
<td>-</td>
<td>Interactions between biochar and slag poor in comparison with other carbonaceous materials. Smooth biochar surface reduced slag foaming.</td>
<td>[30] L</td>
</tr>
<tr>
<td>Foaming</td>
<td>100% biochar 1:1 biochar and coke, additioned with FeO</td>
<td>Foaming time 3–4 s, high reactivity foaming time about 6–9 s.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foaming</td>
<td>50% biochar, 50% coke</td>
<td>Foaming process improved.</td>
<td></td>
<td></td>
<td>[39] L</td>
</tr>
<tr>
<td>Injection, carburization</td>
<td>Biochar from torrefaction, slow pyrolysis, and hydrothermal carbonization; cottonwood pyrolyzed char</td>
<td>100%</td>
<td>No significant negative differences. Combustion reactions were fast and strongly exothermic. Torrefied char: slag foaming promoter cottonwood-derived char: iron carburization.</td>
<td></td>
<td>[35] M</td>
</tr>
<tr>
<td>Injection, charge</td>
<td>Pumpkin seeds</td>
<td>Potential for replacement of charge carbon.</td>
<td></td>
<td></td>
<td>[32] L</td>
</tr>
<tr>
<td>Injection, charge</td>
<td>Grape seeds</td>
<td>Potential to replace injection and charge carbon.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection, charge</td>
<td>Commercial biochar</td>
<td>100%</td>
<td>No deterioration of steel quality.</td>
<td></td>
<td>[34] P</td>
</tr>
<tr>
<td>Melting</td>
<td>Biochar from hydrothermal carbonization</td>
<td>Shorten melting time, no negative influence on the final steel product.</td>
<td></td>
<td></td>
<td>[33] P</td>
</tr>
<tr>
<td>Melting</td>
<td>Palm kernel shells</td>
<td>Chemical energy of the higher volatile content is earlier available during the heat-increased reaction rate of palm kernel shells.</td>
<td></td>
<td></td>
<td>[31] M</td>
</tr>
<tr>
<td>Melting</td>
<td>Loose biochar bio-briquettes</td>
<td>Biobriquettes showed sufficient slag efficiency/protect lining; biochar showed critical characteristics towards a suitable use for slag foaming.</td>
<td></td>
<td></td>
<td>[38] L</td>
</tr>
<tr>
<td>Melting</td>
<td>Pelletized biochar from torrefaction of wood chips Pelletized hydrochar from hydrothermal carbonization of sewage sludge</td>
<td>Feasibility study of a low-temperature molten hydroxide direct carbon fuel cell as additional energy source.</td>
<td>Biochar (powder) showed better performance than hydrochar.</td>
<td></td>
<td>[41] L</td>
</tr>
</tbody>
</table>

Tables’ abbreviations: PC: pulverized coal; PBI: pulverized biomass injection; L: lab scale study; P: pilot scale; M: model; R: review paper; F: full-scale; CSR: coke strength after reaction; CRI: coke reactivity index; GHG: greenhouse gas; MFA: mass flow analysis.
4. Discussion

This review provides an analysis of the possibility of using different biochar sources as a full or partial replacement for carbon or coke in steelmaking processes in the view of moving forward towards the carbon neutrality route.

Biochar can be derived from various sources, including residual biomass, sawdust, wood chips, wood biomass, sunflower husk, agricultural residues, rice husk, coconut shell, raw torrefied biomass, etc. Biochar production undergoes processes such as pyrolysis, gasification, hydrothermal carbonization, and torrefaction, which result in biochar with different properties. Biochar characteristics affect the production quality and energy efficiency, and the possibility of full or partial replacement of coal/coke. These characteristics include the porosity of the biochar, its carbon content, its calorific value, and the ash concentration. Generally, biochar shows lower fixed carbon content and calorific values, higher volatile matter content, and a more porous structure than coal/coke.

The reviewed literature supports the partial substitution of coal/coke with biomass products such as biochar in the steelmaking industry.

In BF, biochar can be mostly used as a partial replacement for injection fuel: although having a low heating value, it demonstrated a faster combustion rate due to its higher content of volatile matter [36]. The literature generally suggests a potential for replacement of approximately 20% overall [14,15,47].

In coke making processes, the substitution percentage settles around 5%, ranging from 1–2% (biochar from sawdust) up to 10–15% (torrefied biochar and charcoal, respectively), since biochar, even providing a high reactivity, could worsen other parameters such as the fluidity, CSR, and CRI [19]. In ore sintering, biochar was also evidenced to perform well in supporting faster combustion. However, optimal performance requires careful control of particle size and pore volume to ensure it does not compromise product quality. Depending on its properties, biochar addition ranged between 20% up to 50%. In the BF, the results prove a potential for partial replacement of the charged coke and a high chance of a complete replacement of PCI.

In EAF applications, biochar can be used in melting, foaming, and as an injectant. Its high reactivity supported slag foaming, while impurities, particle size, and volatile matter content should be controlled so as not to affect the production quality. Models hypothesized up to 100% fossil carbon replacement with biochar, laboratory experiments, and a real plant application tested successfully 50% and 33% substitution, respectively.

As for partial replacement, producing bio-derived materials with optimal chemical and physical properties presents a major challenge in the steel industry. Further research and investigation are needed on biocoke production with appropriate quality for enhancing the coke industry’s utilization of biomass. Moreover, the influence of the biochar characteristics as fossil fuels substitutes and the quality of final steelmaking products represents an area for further investigation.

Steel production is one of the most energy-intensive and CO₂-intensive industries in the world. Recently, the interest in exploring biochar use opportunities as an alternative for coke and coke in the BF and EAF processes is increasing due to its CO₂ reduction potential [49,50].

Biochar was shown to be effective in reducing carbon dioxide emissions across multiple steelmaking processes. The estimated percentage of emission reduction in BF applications ranged 5–15% in iron sintering, 20–50% if considering different overall BF applications, reaching up to almost 70% in modeled macro-level scenarios [48]. For EAF applications, predictions foresaw a GHG emission decrease of about 41%. Recent literature widely acknowledges the direct or indirect utilization of biochar in EAFs as a key driver for reducing emissions. EAF technology is indeed strictly related to electricity use, and bio-based fuels for electricity generation can contribute to the decarbonization of the sector [50].

Authors generally view the replacement of coal or coke with biochar favorably, even if it does not directly result in CO₂ reduction, as the biomass used to produce biochar is considered carbon neutral. Overall, the potential for increasing biochar substitution in BF is
deemed promising compared to EAF, given the environmental advantages, as the volume and impact of BF are nearly three-fourths that of EAFs [48]. While technical feasibility is relevant, there are other factors to be taken into account, such as the ability to produce biochar with the required characteristics in an economically and environmentally sustainable manner. This implies ensuring an adequate supply of biomass, considering factors such as its origin, transportation distances, and the processes involved in its transformation.

The use of biochar, as biomass-based materials, moves in the direction of contributing to decarbonization, such as biofuels, biodiesels, and other biomass-based fossil fuel substitutes [51,52]. However, from a technical point of view, additional pilot and full-scale tests are necessary to validate the values projected by modeled scenarios, especially across different conditions. On the other hand, policy instruments, industrial symbiosis initiatives, financial supporting tools, and organizational strategies are essential to overcoming barriers and facilitating the widespread adoption of fossil fuel replacement [50].

5. Conclusions

The potential of biochar in mitigating CO$_2$ emissions in the steel industry and its diverse environmental and industrial uses is gaining attention in line with the objectives of the European Commission’s Green Deal. As a key policy priority, the Green Deal aims to reduce Europe’s carbon emissions by 30% by 2030. In support of this objective, the steel manufacturing industry is advocating for the adoption of biochar as a promising tool to help lower carbon emissions.

Biochar has emerged as a promising resource with diverse applications in the metallurgical sector. It has been shown to be a viable substitute for coal and coke in numerous steelmaking processes, providing environmental advantages such as CO$_2$ reduction. Laboratory and full-scale studies have demonstrated the success of using biochar to partially replace coal and coke in steelmaking processes, with effectiveness dependent on its specific characteristics and the percentage of replacement. The current review highlights recommended substitution levels for various steelmaking processes and biochar sources as outlined in scientific literature. For example, for the iron ore sintering processes, the substitution must be below 30 wt% if the biochar is sourced from residual biomass, and it should be below 10 wt% if the biochar is sourced from sunflower husk.

Considering that the use of biochar and other biomasses in the metallurgical sector is still an area of research and investigation, biochar properties make it an attractive tool for enhancing steel manufacturing, mitigating climate change, and addressing environmental challenges. Future studies should focus on evaluating the potential of biochar to promote higher substitution percentages and contribute to enhancing energy and production efficiency, as well as measuring effective CO$_2$ emissions reduction. By advancing our understanding of biochar’s production processes, properties, and applications, we can unlock its full potential as a valuable resource in climate change mitigation and environmental management.

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35. Cardarelli, A.; De Santis, M.; Cirilli, F.; Barbanera, M. Computational fluid dynamics analysis of biochar combustion in a simulated ironmaking electric arc furnace. *Fuel* **2022**, *328*, 125267. [CrossRef]
41. Dall’Osto, G.; Mombelli, D.; Pittalis, A.; Mapelli, C. Biochar and other carbonaceous materials used in steelmaking: Possibilities and synergies for power generation by direct carbon fuel cell. *Biomass Bioenergy* **2023**, *177*, 106930. [CrossRef]

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