

Overview of the main pathways for biochar utilization in iron and steelmaking

L. Kieush^{1*}, A. Koveria^{2,3}

¹K1-MET GmbH, Leoben, Austria

²Dnipro University of Technology, Dnipro, Ukraine

³Technical University of Leoben, Leoben, Austria

*Corresponding author: lina.kieush@k1-met.com

Abstract. This paper summarizes the main applications and property requirements of biochar in iron and steel production as a renewable alternative to fossil carbon materials. It discusses its application in cokemaking, iron ore sintering, blast furnace (BF) injection, basic oxygen furnace (BOF), and electric arc furnace (EAF). For each process, the functions of biochar and the requirements for its main properties, reactivity, porosity, density, and mechanical strength are systematized. It is shown that in cokemaking, the biochar share is typically limited to about 10 wt% because it deteriorates coke strength and reactivity. In iron ore sintering, 40-60 wt% of coke breeze can be replaced by biochar, and in BF injection, the substitution level depends on combustion conditions and the need to maintain a stable temperature in the tuyere zone. Biochar has the greatest potential in BOF and EAF, where it can be used as a supplementary energy source, carburizer, and slag foaming agent. The main limitations of industrial biochar application include instability of properties, low density and strength, heterogeneous ash composition, and a tendency to self-heat. It is concluded that specific biochar requirements need to be developed for each metallurgical process.

Keywords: carbon materials, metallurgy, reactivity, biochar, biocoke, iron ore sintering, recarburization, electric furnaces.

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1. Introduction

Carbon materials are practically indispensable components of present pyrometallurgy, which perform a complex range of thermophysical, chemical, and structural-mechanical functions. In metallurgical processes, carbon is the primary source of high-potential thermal energy and the main chemical reducing agent [1, 2]. Under the thermodynamic conditions of smelting, it directly reduces metal oxides and generates carbon monoxide, which indirectly reduces them. In addition, high-carbon materials are irreplaceable in related processes as carburizers for carbonizing the melt to a specified chemical composition, as well as electrically conductive elements in electrothermal and electrolytic aggregates.

Carbon plays a uniquely critical role in the blast furnace (BF) process, where metallurgical coke, in addition to its energy and chemical functions, serves as a drainage agent and helps maintain the structure of the charge materials at high temperatures. With its high hot strength, coke withstands the enormous pressure from the overlying layers under counterflow conditions of materials and gases. At the current stage of technological development, it is not physically or technologically viable to fully replace fossil-based coke in this load-bearing role in large-scale BFs. However, this unalterable dependence is precisely what makes the

metallurgical industry one of the key emitters of anthropogenic greenhouse gases, primarily carbon dioxide.

In the face of stringent climate constraints and the impossibility of completely abandoning carbon-based technology, one key practical avenue for decarbonizing the industry is the accelerated transition to renewable carbon materials [3-6]. The use of biochars allows a drastic reduction in the carbon footprint of metal products. Since biochars are of plant origin, the CO₂ emitted during their use is considered carbon-neutral within the context of a short natural cycle. In the medium term, partially replacing fossil carbon with renewable carbon is the main strategic way for the ecological transformation of traditional metallurgy [7-9].

Depending on the technological process for iron and steel production, the possibilities for integrating biochar vary significantly and are determined by the requirements for the mechanical, chemical, and reactive properties of the carbon-bearing material. Figure 1 shows the ways in which biochar can be used in iron and steelmaking. In the integrated BF–basic oxygen furnace (BOF) process, the potential for replacing fossil carbon is limited. The main issue is that metallurgical coke serves not only as a fuel and reducing agent but also as the skeleton of the charge column to provide gas permeability and effective drainage. Consequently, completely replacing coke with biochar in a BF is currently not feasible.

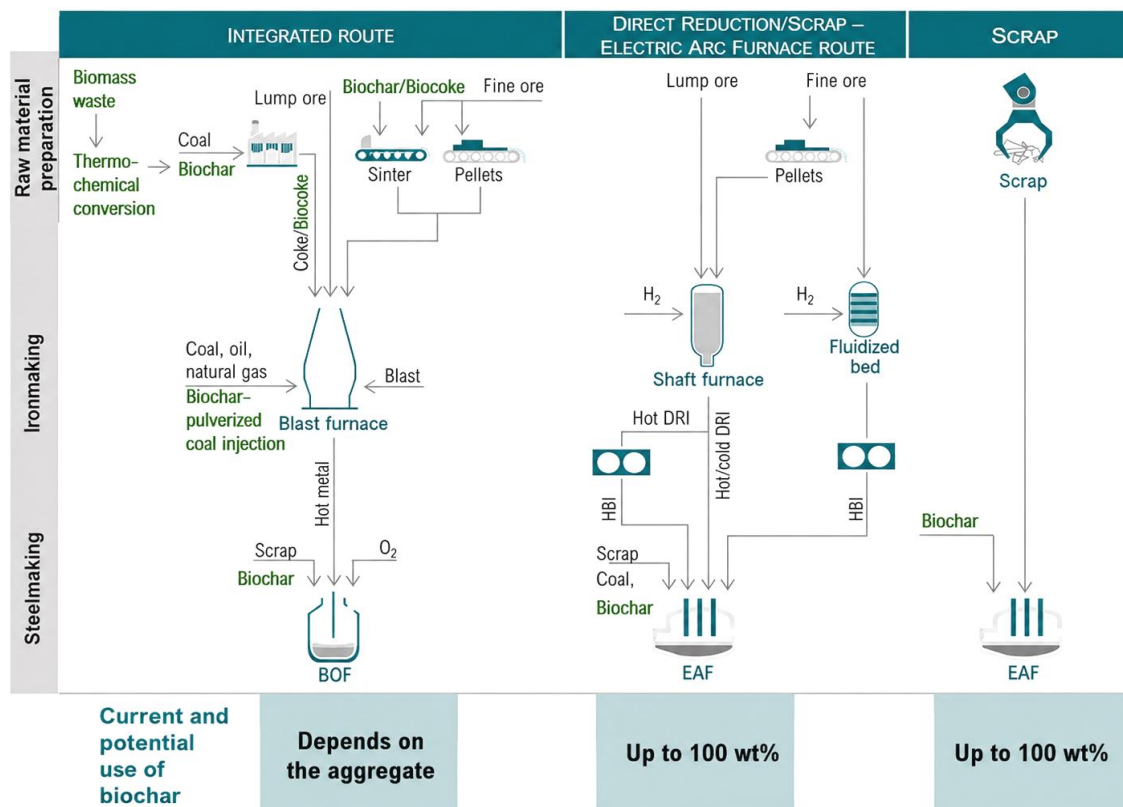


Figure 1. Main pathways for using biochar in iron and steelmaking (adapted from [10])

The most realistic option is to inject pulverized biochar through the tuyeres (pulverized coal injection, PCI), which allows partial replacement of pulverized coal without significantly altering furnace design [11-13]. Additionally, biochar can be used in sintering and pelletizing operations. However, the acceptable extent of its use is determined by the quality requirements for iron ore feedstock and products [14-18].

The greatest potential for biochar integration lies in the route of direct reduced iron (DRI) technologies combined with electric arc furnaces (DRI-EAF), as well as in the production of steel from scrap metal in electric arc furnaces. In direct reduction processes, biochar can be used as a reducing agent and a source of carbon, and in electric arc furnaces as a carburizer, for slag foaming, and as an additional energy source [19-24]. Since these processes do not require preserving the charge structure, the proportion of fossil carbon replaced by biochar can be significantly higher than in BF metallurgy and, in certain operations, could theoretically reach complete replacement.

The effectiveness of carbon materials in metallurgical processes is determined by a combination of their physico-chemical and physico-mechanical properties and microstructure. Biochar properties vary significantly with biomass type, thermo-chemical conversion conditions, and subsequent processing, leading to substantial differences in metallurgical behavior.

Ultimate and proximate analyses provide the primary characterization of carbon materials. Ultimate analysis determines the content of the main chemical elements as carbon, hydrogen, oxygen, nitrogen, and sulfur, which influence the formation of gaseous products, the material's calorific value, and the potential for introducing undesirable impurities into the metal and slag. Proximate analysis includes determining the moisture, volatile matter, and ash, which are the primary indicators of a carbon material's suitability for metallurgical applications.

Ash yield and its chemical composition are particularly important. The mineral phase determines how the carbon material interacts with the slag and metal phases, influences the reactivity and dissolution of carbon, and may either promote the formation of a mineral layer on the particle surface or, conversely, catalyze reactions [25-27]. Therefore, when assessing the potential for biochar use, it is necessary to consider not only the ash amount but also the ratio of acidic to basic oxides, and the presence of catalytically active components, such as potassium, sodium, calcium, and iron compounds.

The structural characteristics of carbon materials play an important role. The type of chemical bonds, the degree of aromatization of the carbon matrix, the microstructure, particle morphology, pore sizes, and the development of the internal surface determine the availability of active sites for heterogeneous reactions. These parameters directly influence the material's reactivity, the rate of iron oxide reduction, the dissolution of carbon in the melt, and other metallurgical processes.

Thermochemical properties, including the kinetics of thermal decomposition, gasification, and oxidation, are also key criteria for evaluating carbon materials. They determine the material's behavior at high temperatures and its ability to effectively function as a fuel, reducing agent, or carburizer in various metallurgical processes.

It should be noted that the individual properties of a carbon material cannot be considered in isolation. Reactivity and mechanical strength are integral characteristics that are shaped by the combined influence of fixed carbon, ash amount and chemistry, degree of graphitization, porous structure, particle morphology, and the material's thermo-chemical behavior. Figure 2 presents a scheme of the main parameters and properties of carbon materials and their inter-relatedness.

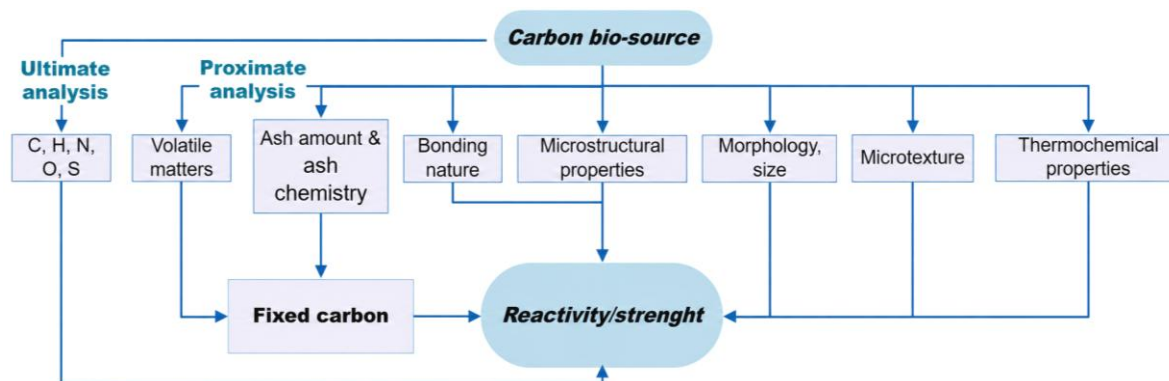


Figure 2. Scheme of the key parameters and properties of carbon materials for iron and steelmaking

2. Biochar utilization in cokemaking

One of the most widely researched areas of biomass and biochar application in the integrated BF-BOF process is its use in cokemaking to produce biocoke. In this approach, biomass or pre-produced biochar is added to the coal charge as a partial substitute for coking coals [28-32]. After co-coking, a composite coke is formed that contains both fossil and renewable carbon. In most studies, the biomass or biochar content in the coal charge is up to 10 wt%. This range allows the biocoke to retain acceptable technological properties. The tolerable degree of substitution is determined by the type of biomass, the temperature of its thermochemical treatment, the volatile matter, the ash value, the chemical composition of the ash, and the material's ability to interact with the plastic phase of the coal during the coking process.

Using biochar in coal blends offers several potential advantages. Biochar typically has a low ash amount and very low sulfur and phosphorus levels compared to coal. As a result, the concentration of undesirable elements in biocoke is reduced. The mineral composition of biochar ash also differs from that of coal ash and can alter the processes involved in the formation of the mineral phase of biocoke, affecting its structure and performance characteristics.

At the same time, increasing the proportion of biochar is accompanied by several technological limitations. Table 1 compares the characteristics of conventional coke and biocoke.

Table 1. Comparison of the general requirements of conventional coke and biocoke

Parameters	Coke	Biocoke
	Values	
Proximate analysis, wt%		
Moisture, ad	<5.0 (wet quenching) <0.7 (dry quenching)	
Volatile matters (VM ^{db}), db	≤1.0	
Ash, db	≤11.0	5.8-10.8
Sulfur (S _t ^{db}), db	<1.0	0.2-1.0
Fixed carbon (fC ^{db}), db	app. 86.0-88.0	app. 87-92
Ultimate analysis, wt%		
Carbon, db	app. 85.0–87.0	app. 84.5–92
Hydrogen, db	app. 0.18–0.4	>0.2
Nitrogen, db	app. 1.0–1.9	~1.0
Oxygen, db	app. 0.2–0.9	~2.0
Other parameters		
Specific surface area (SSA), m ² /g	app. 2.0	app. 2.0-6.0
Coke reactivity index (CRI), %	<25	>25
Coke strength after reaction with CO ₂ (CSR) %	>65	<65

In Table 1, ad denotes the as-determined basis, while db denotes the dry basis. The high volatile content and the unique structure of biochar can lead to a lower yield of solid product during coking. Additionally, biocoke is usually characterized by higher reactivity toward carbon dioxide (coke reactivity index, CRI) and lower coke strength after reaction (CSR). These changes are due to increased porosity, a larger specific surface area, and a less ordered structure of the carbon matrix compared to traditional metallurgical coke.

3. Biochar utilization in iron ore sintering

The sintering process of iron ore is one of the most energy-intensive stages of integrated BF production and produces the sinter for BF. Coke breeze is traditionally used as fuel, providing the necessary heat release as the combustion front moves through the sintering charge layer. In recent years, significant attention has been paid to the possibility of partially replacing coke breeze with biomass, biochar and biocoke in order to reduce fossil carbon consumption and lower greenhouse gas emissions [15, 33-37].

During the sintering process, biochar acts as a fuel, providing the thermal energy necessary for the formation of the liquid phase and the subsequent sintering of iron ore particles. In contrast to coke, biochar cannot support mechanical loads, therefore, the strength requirements for it are significantly lower. However, its effectiveness is determined by a set of physico-chemical characteristics, including fixed carbon, volatile matter, moisture, ash, particle size, bulk density, and calorific value.

To have a stable sintering process, the carbon materials must meet several technological requirements. Moisture should generally not exceed 15 wt%, as high moisture content impairs the granulation of the charge and increases the thermal energy required for water evaporation. It is recommended to keep volatile matter below 3 wt% to maintain a stable combustion front without excessively rapid release of gaseous products. The ash value of the fuel should be less than 12 wt%, since an increase in the amount of mineral impurities leads to an increase in the volume of the slag phase, a change in the mineralogical composition of the sinter, and a decrease in the iron content of the product. Fixed carbon should be in the range of 80-85 wt% to provide the necessary calorific value and combustion duration. Additional requirements include a minimum sulfur content, a particle density of more than 700 kg/m³, a particle size of 0.3-3.0 mm (with a possible increase to 10 mm), and a higher heating value of 25-30 MJ/kg. The main properties of fuel for iron ore sintering are presented in Table 2.

Table 2. Requirements for the properties of fuel for iron ore sintering

Parameters	Value
Moisture, wt%	<15.0
Volatile matters (VM ^{db}), wt%	<3.0
Ash (A ^{db}), wt%	<12.0
Fixed Carbon (fC ^{db}), wt%	80.0-85.0
Sulphur (S _t ^{db}), wt%	<2.0
Particle density, kg/m ³	>700
Size, mm	0.3-3.0 or 10.0

One of the main advantages of biochar is the ability to partially replace coke breeze without modifying the existing sintering technology. According to published studies, the degree of substitution can reach 40-60 wt%. However, the optimal range is determined by the properties of the specific biochar and the quality requirements for the sintered product [14, 38-41]. Experimental data also show that as the degree of substitution of coke breeze with biochars increases, the sinter yield gradually decreases [15, 37, 42]. Despite these limitations, biochar use offers significant environmental benefits. Because it contains almost no fossil carbon, the overall carbon footprint of the sintering process is reduced. In addition, the low sulfur content in most biochar types reduces SO₂ emissions, and the absence of significant bound nitrogen helps reduce NO_x formation. Biochar's high reactivity also allows more complete fuel combustion and reduces unburned carbon emissions.

4. Biochar utilization for injection into a blast furnace

Pulverized Coal Injection (PCI) technology is one of the most effective ways to reduce metallurgical coke consumption in the BF process. In modern BFs, the consumption of injected fuel typically ranges from 150 to 250 kg/t of pig iron, and in the most advanced facilities, it can reach 250 to 300 kg/t of pig iron, which significantly reduces the consumption of expensive coke and lowers production costs [43-46]. In recent years, biochar has been viewed as a promising alternative to fossil pulverized coal fuel due to its renewable origin and virtually neutral carbon balance.

When injected through the BFs' tuyeres, biochar serves two main functions, namely, it acts as an additional source of thermal energy and participates in reduction processes. In the combustion zone, biochar rapidly heats to 1800-2200°C, releasing volatile compounds. The residual carbon then reacts with blast oxygen and carbon dioxide to form CO. The resulting carbon monoxide is the primary reducing agent involved in the reduction of iron oxides in the BF shaft. In contrast to coke, biochar is characterized by significantly higher porosity, a large specific surface area, and greater reactivity, which contributes to its rapid ignition and nearly complete combustion within the confined space of the tuyere zone.

To apply biochar in PCI technology, it should meet several technical requirements. The moisture content before drying must not exceed 15 wt%, and after drying, 2 wt%, since excess moisture increases the energy required for water evaporation and impairs the stability of powder transport in the pneumatic injection system. It is recommended to maintain volatile matter at 20-25 wt% to achieve rapid fuel ignition and preserve sufficient solid carbon for subsequent reduction reactions. Fixed carbon must exceed 75 wt%, and ash should be limited to less than 10 wt% to minimize the introduction of mineral impurities into the BF and prevent deterioration of slag properties. Table 3 lists the main requirements for pulverized coal fuel for injection into a BF.

Table 3. Key requirements for PCI for BF

Parameters	Value
Moisture before drying, wt%	<15.0
Moisture after drying, wt%	<2.0
Volatile matters (VM ^{db}), wt%	<20.0-25.0
Ash (A ^{db}), wt%	<10.0
Fixed Carbon (fC ^{db}), wt%	>75.0
Sulphur (S _t ^{db}), wt%	<0.45-0.5
Phosphorus (P), wt%	<0.05
Alkalis, wt%	<0.3
Ash fusion temperature, °C	1250-1450

Particular attention is paid to harmful impurities. The sulfur concentration must be less than 0.50 wt%, the phosphorus content less than 0.05 wt%, and the total content of alkali elements must be less than 0.3 wt%, since their accumulation in the BF leads to intensified internal circulation of alkalis, accelerated deterioration of refractories, and deterioration of the process's gas dynamics. The melting point of the fuel ash should be in the range of 1250-1450°C, which prevents the formation of molten deposits in the tuyere zone and ensures stable BF operation.

Several factors determine the maximum possible rate of substitution of traditional pulverized coal fuel with biochar. One of the most important factors is the material's grindability. Because of its lower hardness, biochar typically requires less energy to grind than bituminous coal. However, its high porosity leads to the formation of more ultrafine particles, which can complicate powder transportation and alter its combustion characteristics.

Another important characteristic of biochar is its higher oxygen content compared to some bituminous coals. The increased oxygen concentration reduces the fuel's calorific value and lowers the combustion temperature. In the BF process, this effect is compensated for by increasing the oxygen content of the blast air, thereby maintaining a practically constant adiabatic combustion temperature in the tuyere zone (Raceway Adiabatic Flame Temperature, RAFT). Maintaining RAFT is a prerequisite for stable furnace operation and maintaining productivity as the proportion of biochar increases. As the rate of fossil coal substitution with biochar increases, it is necessary to optimize the blast parameters, oxygen flow rate, and fuel injection regime.

5. Biochar utilization in the basic oxygen furnace process

Basic oxygen steelmaking remains the dominant steelmaking process and forms part of the BF-BOF route, which accounts for approximately 70% of global crude steel production [9, 47]. During BOF refining, oxygen is blown onto and/or into a bath of hot metal containing steel scrap and fluxes, promoting the oxidation of carbon, silicon, manganese, phosphorus, and other elements. These exothermic reactions provide the heat required to refine and melt the added scrap. Despite the autothermal nature of the process, additional energy sources are often used to maintain the required heat balance to allow a higher proportion of scrap metal in charge and reduce liquid pig iron consumption.

One promising renewable source of additional energy is biochar. In an oxygen converter, it serves as both a fuel and a carbon-containing material, the oxidation of which is accompanied by the release of a significant amount of thermal energy. The requirements for its mechanical strength can be significantly lower, while its chemical composition, ignition rate, and oxidation kinetics become the key factors.

When biochar is introduced into the melt, its particles rapidly heat to 1600-1700°C, after which intense oxidation of carbon by oxygen begins, primarily forming carbon monoxide. The following exothermic reactions take place, according to Equations 1 and 2:



These reactions provide an additional heat input to the converter, contributing to maintaining the required temperature of the molten steel without increasing the consumption of molten pig iron. The high porosity of biochar and its large internal surface area ensure rapid ignition and a high rate of oxidation compared to traditional fossil carbon materials.

The additional thermal energy compensates for the loss of physical heat that occurs when the scrap metal content in the charge is increased [48-51]. Increasing the scrap content is one of the most effective ways to reduce total CO₂ emissions, as steel production from recycled metal results in a significantly smaller carbon footprint compared to the use of molten pig iron.

The use of biochar reduces the consumption of traditional chemical energy sources used to regulate the converter's heat balance, such as ferrosilicon, aluminum, coke breeze, or anthracite. Thus, a portion of fossil carbon can be replaced with a renewable alternative without significantly altering existing steel production technology.

For effective use in a BOF, biochar moisture should not exceed 2 wt%, as its evaporation leads to additional heat losses and impairs the stability of the material feed. It is recommended to limit volatile matter to 3-6 wt% to have a sufficient ignition rate with minimal release of gaseous products. Ash should be less than 10 wt% to prevent excessive influx of mineral components into the slag and avoid increased flux consumption. Fixed carbon should typically be around 75-90 wt% to possess a high calorific value and efficient use of the material as a source of chemical energy. Table 4 lists the main requirements for fuel used in the BOF process.

Table 4. The main requirements for fuel in BOF

Parameters	Value
Moisture, wt%	<2.0
Volatile matters (VM ^{db}), wt%	<3.0-6.0
Ash (A ^{db}), wt%	<10.0
Fixed Carbon (fC ^{db}), wt%	75.0-90.0
Sulphur (S ^{db}), wt%	<0.6
Phosphorus (P), wt%	low
Alkalis, wt%	low
Density, kg/m ³	>500

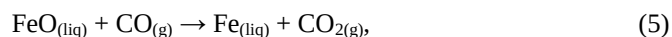
Special attention is paid to the concentration of harmful impurities. The sulfur value should be less than 0.6 wt%, and the content of phosphorus and alkali elements should be kept to a minimum, as their presence degrades steel quality, increases the load on refining processes, and may negatively affect the durability of the refractory lining. It can be advised to maintain biochar density above 500 kg/m³ to reduce dust generation.

6. Biochar utilization in electric arc furnaces

The EAF is the primary unit for producing steel from scrap metal and direct reduced iron (DRI/HBI). Compared to the integrated BF route, the main energy source in the EAF is electricity. However, carbon-based materials remain a critical

component of the process [14, 28, 52-54]. They reduce iron oxides, recarburize molten steel, and provide additional chemical energy through exothermic carbon oxidation reactions. Because carbon materials do not require high mechanical strength, biochar is considered one of the most promising renewable substitutes for fossil carbon, particularly in electric arc metallurgy.

In modern EAFs, carbon can be introduced either as part of the metal charge or by injecting powdered material. Biochar can perform both functions, making it possible to partially or nearly completely replace traditional carbon materials in certain process operations. One of the most important functions of carbon in an EAF is slag foaming [19, 21, 55-57]. During melting, the slag contains some amount of iron oxide (FeO), which reacts with carbon and can also react with CO, according to Equations 3 and 5. Additionally, some reactions can occur with carbon according to Equations 4 and 6.



The generated carbon monoxide causes slag foaming. The foamy slag covers the electric arcs, reducing heat loss through radiation, protecting the furnace lining, and ensuring more uniform heat distribution throughout the melt. As a result, specific electricity consumption decreases, the electrical energy utilization factor improves, and the service life of the refractories is extended.

On average, 10-20 kg of carbon per metric ton of steel is required for effective slag foaming, although actual consumption depends on slag composition, FeO content, oxygen blowing regime, and the technology used at a specific metallurgical plant. Because of biochar's high reactivity, CO formation occurs more rapidly than when using traditional coke breeze, which promotes more intense slag foaming. However, excessively high reactivity can lead to foam instability, so biochar properties should be adapted to the process conditions.

Another important function of biochar is related to the reduction of iron oxides present in the slag. During oxygen blowing, some of the iron inevitably ends up in the slag as FeO. The reduction reaction allows the iron to return to the metal bath, increasing the yield of usable metal and reducing iron losses in the slag. The efficiency of this process is determined by the reactivity of the carbon, its surface area, and the rate of CO reduction gas formation.

Biochar is also widely considered as a material for the recarburization of molten steel or steel alloying [20, 24, 58]. After the period of intensive oxidation ends, the carbon content in the metal is usually lower than required, so additional recarburization of the melt can be carried out to achieve the required chemical composition of the steel. In this case, carbon should also dissolve effectively in the molten metal. Typically, carbon-bearing material consumption during the recarburization stage is 2-5 kg per metric ton of steel. However, specific values depend on the steel grade and the final carbon content.

Overall, total consumption of carbon-containing materials in an EAF is approximately 12-25 kg per metric ton of steel produced, including materials for slag foaming and recarburization. When transitioning to DRI-EAF technology, carbon demand may increase due to the higher iron oxide content in the metalized source.

To use biochar effectively in an EAF, it should meet the basic requirements listed in Table 5. It is recommended to keep moisture below 2 wt%. Volatile matter is typically limited to 2-7 wt%. Fixed carbon should exceed 80-85 wt%, while ash should be limited to less than 10 wt% to avoid excessive slag volume and changes in physico-chemical properties. Sulfur and phosphorus concentrations should be kept to a minimum, as these elements can transfer into the metal and degrade steel quality. The optimal particle size is approximately 0.5-5 mm.

Table 5. Basic requirements for carbon materials for use in EAFs

Parameters	Value
Moisture, wt%	1.0-7.0
Volatile matters (VM ^{db}), wt%	2.0-7.0
Ash (A ^{db}), wt%	<10.0
Fixed Carbon (fC ^{db}), wt%	>85.0
Sulphur (S _t ^{db}), wt%	low
Phosphorus (P), wt%	low
Size, mm	0.5-5.0

The effectiveness of biochar in EAF conditions depends on a combination of its physico-chemical properties. The most significant factors are fixed carbon, reactivity, particle size distribution, porosity, degree of microstructural development, volatile matter, and ash chemistry. High porosity increases reaction surface area and accelerates FeO reduction. However, it can also reduce particle mechanical strength and alter the rate of carbon dissolution in the metal. The mineral components of the ash can catalyze gasification reactions and alter the slag's composition and viscosity, thereby affecting the stability of the foam layer.

An important advantage of biochar is its high reactivity compared to coke breeze, petroleum coke, and anthracite [52, 59, 60]. Because biochar has a more developed porous structure and more active sites, it participates in reduction and gasification reactions more quickly, improving slag foaming efficiency and reducing melting time. At the same time, excessive reactivity can accelerate carbon consumption and reduce process stability. Therefore, different biochar characteristics may be required for various operations (e.g., slag foaming, recarburization).

7. Outlook

Despite biochar's significant potential as a renewable carbon source for metallurgical processes, its widespread industrial adoption faces several scientific, technical, and technological challenges. Unlike traditional fossil carbon materials, whose properties are relatively stable and standardized, biochar characteristics depend heavily on biomass origin, growing conditions, pretreatment technology, and pyrolysis and post-furnace treatment parameters. This variability makes it difficult to predict the material's behavior under high-temperature metallurgical conditions and requires new approaches to classification and standardization.

One of the main challenges is the variability of biochar's physico-chemical properties. Even with a single biomass type, fixed carbon can vary widely (60 to over 90 wt%), ash from less than 1 to over 10 wt%, and volatile matter from 5 to 30 wt%, depending on pyrolysis temperature. Similarly, the specific surface area, porosity, density, degree of order, and chemical composition of the ash vary significantly. This heterogeneity complicates the direct replacement of fossil carbon materials and requires selecting biochar for each metallurgical process.

Special attention is given to the relatively low mechanical strength and density of biochars. Depending on the feedstock, biochar density typically ranges from 200 to 600 kg/m³, which is significantly lower than that of metallurgical coke (700-900 kg/m³). Increased brittleness contributes to fine-particle formation during transportation and storage, impairs dosing conditions, and limits the use of biochar in processes where the material is subjected to significant mechanical stress. Therefore, densifying biochar is essential for improving its application efficiency.

High oxygen and hydrogen content also significantly affects the metallurgical behavior of biochar. Although oxygen-containing functional groups increase the material's reactivity, they also reduce its calorific value and increase the rate of gasification. Furthermore, an increase in the content of volatile matter can lead to changes in the fuel's combustion characteristics and a redistribution of heat fluxes in metallurgical units.

In some cases, the chemical composition of the ash poses an additional limitation. Various types of biomass may contain elevated concentrations of alkali metals (K, Na), calcium, magnesium, silicon, and phosphorus. These elements have a significant impact on reactivity, slag formation, high-temperature corrosion of equipment, and the quality of metal products. Controlling the content of phosphorus and alkali elements is particularly important, as their accumulation can negatively affect the technological characteristics of the metallurgical process.

At the same time, the high variability of biochar's properties opens up significant opportunities for its targeted adaptation to specific metallurgical processes. Unlike fossil carbon materials, biochar properties can be controlled as early as the production stage by selecting the feedstock and adjusting the pyrolysis temperature and duration, heating rate, process atmosphere, and post-treatment methods. This approach allows the production of materials with predetermined characteristics optimized for specific technological tasks.

One of the most promising areas of research is developing function-oriented requirements for biochar. It is advisable to determine specific quality criteria for each metallurgical process. An equally important area of research involves studying the mechanical strength of biochar, as well as its behavior during transportation and long-term storage. For industrial applications, it is necessary to determine the mechanisms of particle fracture, the material's susceptibility to abrasion and dust formation, the effect of ambient humidity on property changes, and the possibility of compacting the material through briquetting or granulation. Increasing biochar density can significantly improve conditions for transportation, storage, dosing, and use in metallurgical production.

Special attention should be paid to industrial safety issues. Due to their high specific surface area and increased reactivity, some types of biochar may be prone to self-heating and spontaneous combustion, especially after drying or when stored in the presence of oxygen [61-63]. This effect is caused by intense oxidation of active surface sites and may pose a hazard during transportation and storage. Therefore, for each type of biochar, it is necessary to determine the oxidation onset temperature, the kinetics of self-heating, and the conditions for safe storage.

Meanwhile, variability in biochar properties can be a significant advantage. Depending on the biomass type and processing technology used, it is possible to produce materials

with low ash, minimal sulfur and nitrogen content, high fixed carbon content, and optimal reactivity. This opens opportunities to create specialized biochar for various ferrous metallurgy processes, allowing not only reduced fossil carbon consumption but also improved production performance metrics.

7. Conclusions

The study shows that biochar is one of the most promising renewable carbon materials for defossilizing the ferrous metallurgy industry. Because it can be produced from various types of biomasses, is highly reactive, and has a practically neutral biogenic carbon cycle, biochar can partially or completely replace traditional fossil carbon materials in metallurgical processes. However, its effectiveness depends significantly on the specific technology's requirements and the material's complex physico-chemical properties.

In the cokemaking process, biochar can be used as a component of the coal blend to produce biocoke. However, most studies show that the acceptable biochar content is typically up to 10 wt%, since a further increase in its proportion leads to a decrease in the plasticity of the coal mixture, a reduction in the degree of development of the anisotropic coke structure, an increase in CRI, and a decrease in CSR. At the same time, the use of biochar makes it possible to reduce the sulfur and phosphorus content in biocoke and to lower its ash.

The iron ore sintering process offers more favorable conditions for using biochar as a fuel in place of coke breeze. According to established practices, the optimal substitution rate is typically 40-60 wt%, which keeps the yield of usable sinter above 80% while reducing fossil carbon consumption. An additional benefit is reduced CO₂, SO₂, and NO_x emissions due to the low sulfur and nitrogen content in the biomass.

PCI technology also represents a promising way for integrating biochar into BF production. In this technology, biochar serves as both a fuel and a reducing agent, and the absence of requirements for high mechanical strength makes it possible to partially replace traditional pulverized coal. However, the maximum permissible substitution rate is determined by oxygen and volatile matter content, particle size distribution, grindability, and the need to maintain the adiabatic combustion temperature in the BF zone to provide process stability.

Biochar shows significantly greater potential for use in the BOF process, where it can effectively serve as an additional source of chemical energy, thereby reducing the consumption of traditional energy sources, offsetting the decline in the heat balance caused by an increase in the proportion of scrap metal, and thus improving the resource efficiency of steel production.

Promising areas for the industrial application of biochar include EAF. It can be used for slag foaming, reducing iron oxides, recarburizing molten steel, and as an additional source of chemical energy. Depending on the process operation and material characteristics, it is possible to partially or nearly completely replace traditional carbon materials with renewable carbon.

Author contributions

Conceptualization: LK, AK; Data curation: LK, AK; Formal analysis: LK, AK; Funding acquisition: AK; Investigation: LK, AK; Methodology: LK, AK; Project administration: AK; Resources: LK, AK; Supervision: LK, AK; Validation: LK, AK; Visualization: LK; Writing – original draft: LK, AK; Writing – review & editing: LK, AK. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

References

- [1] Al Hosni, S., Domini, M., Vahidzadeh, R., & Bertanza, G. (2024). Potential and environmental benefits of biochar utilization for coal/coke substitution in the steel industry. *Energies*, 17(11), 2759. <https://doi.org/10.3390/en17112759>
- [2] Bazaluk, O., Kieush, L., Koveria, A., Schenk, J., Pfeiffer, A., Zheng, H., & Lozynskyi, V. (2022). Metallurgical coke production with biomass additives: Study of biocoke properties for blast furnace and submerged arc furnace purposes. *Materials*, 15(3), 1147. <https://doi.org/10.3390/ma15031147>
- [3] Biswal, P., Avdijaj, J., Parente, A., & Coussement, A. (2026). Decarbonization of iron and steel industries: A review of computational advancements to enhance furnace energy efficiency in the BF-BOF route. *Next Energy*, 11, 100578. <https://doi.org/10.1016/j.nxener.2026.100578>
- [4] Chernyatevych, A., Pokhvalitii, A., Kondrashenkov, D., Vovk, A., & Kruty, A. (2026). Review of methods for increasing the scrap ratio and developing preliminary scrap preheating modes in a basic oxygen converter. *Collection of scholarly papers of Dniprovsk State Technical University (Technical Sciences)*, 1(48), 21-27. <https://doi.org/10.31319/2519-2884.48.2026.2>
- [5] Chiew, Y.L., Wetterlund, E., & Lagerkvist, A. (2025). Industrial symbiosis via hydrothermal carbonisation: An environmental and techno-economic assessment in Sweden. *Renewable and Sustainable Energy Transition*, 8, 100129. <https://doi.org/10.1016/j.rset.2025.100129>
- [6] Della Rocca, A. (2025). A perspective on the decarbonization of the metals industry. *Applications in Energy and Combustion Science*, 21, 100312. <https://doi.org/10.1016/j.jaecs.2024.100312>
- [7] Durango Padilla, E.R., Hansted, F.A.S., Luna, C.M.R., de Campos, C.I., & Yamaji, F.M. (2024). Biochar derived from agricultural waste and its application as energy source in blast furnace. *Renewable Energy*, 220, 119688. <https://doi.org/10.1016/j.renene.2023.119688>
- [8] Fan, Z., & Friedmann, S.J. (2021). Low-carbon production of iron and steel: Technology options, economic assessment, and policy. *Joule*, 5(4), 829-862. <https://doi.org/10.1016/j.joule.2021.02.018>
- [9] Gan, M., Fan, X., Ji, Z., Chen, X., Jiang, T., & Yu, Z. (2014). Effect of distribution of biomass fuel in granules on iron ore sintering and NO_x emission. *Ironmaking & Steelmaking*, 41(6), 430-434. <https://doi.org/10.1179/1743281213Y.0000000138>

- [10] Han, J., Xiong, Q., Jiang, K., Jin, H., & Guo, L. (2026). Production, modification and application of biochar in iron and steel metallurgy. *Biomass and Bioenergy*, 215, 109523. <https://doi.org/10.1016/j.biombioe.2026.109523>
- [11] Jha, G., Soren, S., & Deo Mehta, K. (2020). Partial substitution of coke breeze with biomass and charcoal in metallurgical sintering. *Fuel*, 278, 118350. <https://doi.org/10.1016/j.fuel.2020.118350>
- [12] Kawaguchi, T., & Hara, M. (2013). Utilization of biomass for iron ore sintering. *ISIJ International*, 53(9), 1599-1606. <https://doi.org/10.2355/isijinternational.53.1599>
- [13] Khaustova, V., Hubarieva, I., Salashenko, T., Kotliarov, Y., & Ilyash, O. (2026). Transformation of global iron metallurgy in the context of global decarbonization and energy transition. *Ukrainian Journal of Applied Economics and Technology*, 11(1), 425-435. <https://doi.org/10.36887/2415-8453-2026-1-82>
- [14] Kieush, L., Koveria, A., Boyko, M., Hrubyak, A., Sova, A., & Yefimenko, V. (2021). Walnut shells as a potential fuel for iron ore sintering. *Materials Science Forum*, 1045, 127-140. <https://doi.org/10.4028/www.scientific.net/MSF.1045.127>
- [15] Kieush, L., Koveria, A., Boyko, M., Yaholnyk, M., Hrubyak, A., Molchanov, L., & Moklyak, V. (2022). Influence of biocoke on iron ore sintering performance and strength properties of sinter. *Mining of Mineral Deposits*, 16(2), 55-63. <https://doi.org/10.33271/mining16.02.055>
- [16] Kieush, L., Koveria, A., Huynh, T.P., Zuber, J., Vogt, C., & Smätt, J.H. (2025). Comprehensive microstructural evaluation of biochar, biocoke, and anthracite with respect to the CO₂ reactivity. *Results in Engineering*, 27, 105690. <https://doi.org/10.1016/j.rineng.2025.105690>
- [17] Kieush, L., Koveria, A., Zhu, Z. Q., Boyko, M., Sova, A., & Yefimenko, V. (2021). Application of biomass pellets for iron ore sintering. *Materials Science Forum*, 1045, 17-31. <https://doi.org/10.4028/www.scientific.net/MSF.1045.17>
- [18] Kieush, L., Molchanov, L., Koveria, A., Golub, T., Huynh, T.P., Smätt, J.H., Pötschke, D.M., Zuber, J., & Vogt, C. (2026). Steel recarburization by densified and nondensified biochar as a carburizing agent in electric arc furnace-based steelmaking. *Steel Research International*, 70605 <https://doi.org/10.1002/srin.70605>
- [19] Kieush, L., Rieger, J., Schenk, J., Brondi, C., Rovelli, D., Echterhof, T., Cirilli, F., Thaler, C., Jaeger, N., Snaet, D., Peters, K., & Colla, V. (2022). A comprehensive review of secondary carbon bio-carriers for application in metallurgical processes: Utilization of torrefied biomass in steel production. *Metals*, 12(12), 2005. <https://doi.org/10.3390/met12122005>
- [20] Kieush, L., & Schenk, J. (2025). Influence of carbon material properties on slag-foaming dynamics in electric arc furnaces: A review. *steel research international*, 96(8), 2400235. <https://doi.org/10.1002/srin.202400235>
- [21] Kieush, L., Schenk, J., Koveria, A., & Hrubyak, A. (2024a). Biocoke thermochemical properties for foamy slag formations in electric arc furnace steelmaking. *Metals*, 14(1), 13. <https://doi.org/10.3390/met14010013>
- [22] Kieush, L., Schenk, J., Koveria, A., & Hrubyak, A. (2024b). Insight into the slag foaming behavior utilizing biocoke as an alternative carbon source in electric arc furnace-based steel production. *Journal of Sustainable Metallurgy*, 10(1), 26-40. <https://doi.org/10.1007/s40831-024-00783-9>
- [23] Kieush, L., Schenk, J., Koveria, A., Rantitsch, G., Hrubyak, A., & Hopfinger, H. (2023). Utilization of renewable carbon in electric arc furnace-based steel production: Comparative evaluation of properties of conventional and non-conventional carbon-bearing sources. *Metals*, 13(4), 722. <https://doi.org/10.3390/met13040722>
- [24] Kim, J., Sovacool, B.K., Bazilian, M., Griffiths, S., Lee, J., Yang, M., & Lee, J. (2022). Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options. *Energy Research & Social Science*, 89, 102565. <https://doi.org/10.1016/j.erss.2022.102565>
- [25] Kim, M.W., Ku, M.J., Kim, J., Kim, G.M., Jeon, C.H., & Lee, D.G. (2026). Towards carbon-neutral ironmaking: Stepwise integration of biocarbon in PCI with combustion behavior characterization and injection limit evaluation. *Engineering*, 59, 215-228. <https://doi.org/10.1016/j.eng.2025.12.004>
- [26] Koveria, A., Kieush, L., Boyko, M., Yaholnyk, M., & Poliakova, N. (2021). Production of iron ore pellets by utilization of sunflower husks. *Acta Metallurgica Slovaca*, 27(4), 167-171. <https://doi.org/10.36547/ams.27.4.1052>
- [27] Koveria, A., Kieush, L., Saik, P., & Lozynskyi, V. (2024). Metallurgical coke production with biomass additives. Part 2: Production and characterization of laboratory biocokes. *Studies in Systems, Decision and Control*, 287-306. https://doi.org/10.1007/978-3-031-44351-0_15
- [28] Kuangdi, X. (Ed.). (2024). *The ECPH encyclopedia of mining and metallurgy*. Springer Nature Singapore. <https://doi.org/10.1007/978-981-99-2086-0>
- [29] Legemza, J., Fröhlichová, M., & Findorák, R. (2019). *Biomass and carbon fuels in metallurgy*. CRC Press. <https://doi.org/10.1201/9780429274039>
- [30] Li, Z., Zhang, J., Wang, Y., & Liu, Z. (2026). Alternative application of biomass fuel in iron ore sintering: Effects on fuel utilization and combustion efficiency. *Minerals Engineering*, 235, 109893. <https://doi.org/10.1016/j.mineng.2025.109893>
- [31] Liu, C., Kang, Y., Zhang, Y., Xing, H., & Xue, G. (2022). Effect of replacing coke with biomass fuel on sinter properties and pollutant emissions. *Metals*, 12(9), 1483. <https://doi.org/10.3390/met12091483>
- [32] Liu, Y., & Shen, Y. (2021). Modelling and optimisation of biomass injection in ironmaking blast furnaces. *Progress in Energy and Combustion Science*, 87, 100952. <https://doi.org/10.1016/j.pecs.2021.100952>
- [33] Lu, X., Chen, M., Zhao, S., & Zhang, Z. (2026). Progress in transition-metal-catalyzed C-H functionalization of 2-arylthiazoles and 2-arylbenzothiazoles. *European Journal of Organic Chemistry*, 29(14), e202501221. <https://doi.org/10.1002/ejoc.202501221>
- [34] Lytvynuk, Y., Shatokha, V., & Zajac, M. (2023). Increased scrap utilization in converter steelmaking. *Millennium Steel*, 29-35.
- [35] Madhavan, N., Brooks, G.A., Rhamdhani, M.A., Rout, B.K., & Overbosch, A. (2022). Potential for increased scrap melting in a BOF. *AISTech 2022 Conference Proceedings*, PR-386-050.
- [36] Medeiros, G.E., Carbajal Ccoyllo, M.D., de Siqueira, R.N.C., & Ghosh, A. (2026). Alternative carbon sources as foaming agents for electric arc furnace steelmaking slags: A comprehensive review. *Minerals*, 16(2), 152. <https://doi.org/10.3390/min16020152>
- [37] Nayak, D., Nayak, S., Ayyandurai, A., Sathish, R., Dash, N., & Rath, S.S. (2025). Biochar as a sustainable alternative to conventional carbon additives in iron ore pelletization. *Fuel*, 402, 136063. <https://doi.org/10.1016/j.fuel.2025.136063>
- [38] Niesler, M., Stecko, J., Stelmach, S., & Kwiecińska-Mydlak, A. (2021). Biochars in iron ores sintering process: Effect on sinter quality and emission. *Energies*, 14(13), 3749. <https://doi.org/10.3390/en14133749>
- [39] Ohno, K.I., Babich, A., Mitsue, J., Maeda, T., Senk, D., Gudenau, H.W., & Shimizu, M. (2012). Effects of charcoal carbon crystallinity and ash content on carbon dissolution in molten iron and carburization reaction in iron-charcoal composite. *ISIJ International*, 52(8), 1482-1488. <https://doi.org/10.2355/isijinternational.52.1482>
- [40] Panwar, N.L., Gajera, B., Jain, S., & Salvi, B.L. (2020). Thermogravimetric studies on co-pyrolysis of raw/torrefied biomass and coal blends. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, 38(11), 1259-1268. <https://doi.org/10.1177/0734242X19896624>
- [41] Reinmöller, M., Schreiner, M., Laabs, M., Scharm, C., Yao, Z., Guhl, S., Neuroth, M., Meyer, B., & Gräbner, M. (2023). Formation and transformation of mineral phases in biomass ashes and evaluation of the feedstocks for application in high-temperature processes. *Renewable Energy*, 210, 627-639. <https://doi.org/10.1016/j.renene.2023.04.072>
- [42] Ren, S., Yang, S., Chen, H., Wang, L., Liu, M., Wang, G., & Xu, C. (2025). A state-of-the-art review on the utilization of biochar as

- renewable energy for the sustainable steel industry. *Applied Energy*, 394, 126188. <https://doi.org/10.1016/j.apenergy.2025.126188>
- [43] Restuccia, F., Mašek, O., Hadden, R. M., & Rein, G. (2019). Quantifying self-heating ignition of biochar as a function of feedstock and the pyrolysis reactor temperature. *Fuel*, 236, 201-213. <https://doi.org/10.1016/j.fuel.2018.08.141>
- [44] Robinson, R., Brabie, L., Pettersson, M., Amovic, M., & Ljunggren, R. (2022). An empirical comparative study of renewable biochar and fossil carbon as carburizer in steelmaking. *ISIJ International*, 62(12), 2522-2528. <https://doi.org/10.2355/isijinternational.ISIJINT-2020-135>
- [45] Rytty, S., Hoikkaniemi, E., Koskela, A., Sulasalmi, P., Fabritius, T., & Visuri, V.V. (2026). Biochar as a slag foaming agent in simulated EAF conditions: Effect of fixed-C content of biochar and basicity of slag. *Metallurgical and Materials Transactions B*, 57(5), 2852-2865. <https://doi.org/10.1007/s11663-026-04003-5>
- [46] Safarian, S. (2023). To what extent could biochar replace coal and coke in steel industries? *Fuel*, 339, 127401. <https://doi.org/10.1016/j.fuel.2023.127401>
- [47] Sarker, T.R., Ethen, D.Z., & Nanda, S. (2024). Decarbonization of metallurgy and steelmaking industries using biochar: A review. *Chemical Engineering & Technology*, 47(12), e202400217. <https://doi.org/10.1002/ceat.202400217>
- [48] Schwarzer, L., Jensen, P.A., Wedel, S., Glarborg, P., Karlström, O., Holm, J.K., & Dam-Johansen, K. (2021). Self-heating and thermal runaway of biomass – lab-scale experiments and modeling for conditions resembling power plant mills. *Fuel*, 294, 120281. <https://doi.org/10.1016/j.fuel.2021.120281>
- [49] Shi, N., Xie, Y., Watson, P., Wu, Z., Xu, X., Buntine, M., Wu, H., & Shao, Z. (2026). Green steel production: An overview. *Green Chemistry*, 28(21), 8667-8693. <https://doi.org/10.1039/D6GC01497F>
- [50] Somasundaram, S., Congo, T., & Steel, K.M. (2025). Biocoke: Carrying capacity of coking coals for sugarcane bagasse char in terms of viscoelastic behaviour during co-carbonization. *Fuel*, 393, 134903. <https://doi.org/10.1016/j.fuel.2025.134903>
- [51] Soprych, P., & Czerski, G. (2025). The use of biomass ash as a catalyst in the gasification process – a review. *Energies*, 18(21), 5653. <https://doi.org/10.3390/en18215653>
- [52] Uwaoma, R.C., Goso, X.C., Lekgau, K.E., Khama, M.I., & Matinde, E. (2026). Solid-state reduction of titaniferous magnetite ore using coke, anthracite, and charcoal as reductants. *Metals*, 16(5), 479. <https://doi.org/10.3390/met16050479>
- [53] Vassilev, S.V., Vassileva, C.G., Velyanova, G.G., Georgieva, M.G., & Petkova, V. (2026). Content, association, modes of occurrence, and significance of potassium in biomass and biomass ash. *Journal of the Energy Institute*, 126, 102497. <https://doi.org/10.1016/j.joei.2026.102497>
- [54] Voraberger, B., Wimmer, G., Dieguez Salgado, U., Wimmer, E., Pastucha, K., & Fleischanderl, A. (2022). Green LD (BOF) steelmaking – reduced CO₂ emissions via increased scrap rate. *Metals*, 12(3), 466. <https://doi.org/10.3390/met12030466>
- [55] Wang, C., Larsson, M., Lövgren, J., Nilsson, L., Mellin, P., Yang, W., Salman, H., & Hultgren, A. (2014). Injection of solid biomass products into the blast furnace and its potential effects on an integrated steel plant. *Energy Procedia*, 61, 2184-2187. <https://doi.org/10.1016/j.egypro.2014.12.105>
- [56] Wang, G., Wu, J., Zhang, H., Li, D., Ning, X., Liang, W., & Wang, C. (2026). CFD-based comparative assessment of lance configurations for natural gas and pulverized coal co-injection in the blast furnace tuyere-raceway. *International Journal of Hydrogen Energy*, 264, 156893. <https://doi.org/10.1016/j.ijhydene.2026.156893>
- [57] Wang, J., Meng, H., & Zhou, H. (2023). Effect of biochar substitution on iron ore sintering characteristics based on optimization of fuel distribution through the bed. *Fuel Processing Technology*, 247, 107817. <https://doi.org/10.1016/j.fuproc.2023.107817>
- [58] Wang, L., & Skreiberg, Ø. (2023). A critical review on self-heating and self-ignition of biocarbon. *Chemical Engineering Transactions*, 105, 271-276. <https://doi.org/10.3303/CET23105046>
- [59] Wang, L., Yang, Y., Ou, Y., Dong, Y., Zhong, Q., Zhang, Y., Li, Q., Huang, Z., & Jiang, T. (2024). Enhancement of coal tar pitch carbonization with biochar: A metallurgical formed biocoke product produced by waste coke breeze and bamboo powder. *Fuel*, 358, 130238. <https://doi.org/10.1016/j.fuel.2023.130238>
- [60] Watari, T., & McLellan, B. (2024). Decarbonizing the global steel industry in a resource-constrained future – a systems perspective. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 382(2284), Article 20230233. <https://doi.org/10.1098/rsta.2023.0233>
- [61] Wei, R., Zheng, X., Zhu, Y., Feng, S., Long, H., & Xu, C.C. (2024). Hydrothermal bio-char as a foaming agent for electric arc furnace steelmaking: Performance and mechanism. *Applied Energy*, 353, 122084. <https://doi.org/10.1016/j.apenergy.2023.122084>
- [62] Xing, X., Jahanshahi, S., Yang, J., & Ostrovski, O. (2018). Dissolution of carbon from coke and char in liquid Fe–C alloys. *Archives of Materials Science and Engineering*, 92(1), 22-27. <https://doi.org/10.5604/01.3001.0012.5508>
- [63] Zhao, P., Xu, R., Zhang, J., Yu, A., Guo, P., Hu, Z., & Jia, G. (2025). Numerical simulation research on the co-combustion of biochar and pulverized coal in the raceway of blast furnace. *Energy*, 314, 134310. <https://doi.org/10.1016/j.energy.2024.134310>

Шойын және болат өндірісінде биокөмірді пайдаланудың негізгі бағыттарына шолу

Л. Кеуш^{1*}, А. Коверя^{2,3}

¹K1-MET GmbH, Леобен, Австрия

²Ұлттық «Днепровск политехникасы» техникалық университеті, Днепр, Украина

³Леобен техникалық университеті, Леобен, Австрия

*Корреспонденция үшін автор: ling.kieush@k1-met.com

Андатпа. Осы мақалада биокөмірді шойын және болат өндірісінде қолданудың негізгі бағыттары, сондай-ақ оның қазба негізіндегі көміртекті материалдарға жаңартылатын балама ретіндегі қасиеттеріне қойылатын талаптар жинақталған. Биокөмірді кокстеу, темір кенін агломерациялау, домна пешіне (ДП) үрлеу, оттекті-конвертерлік балқыту (ОКБ) және доғалы болат балқыту пешіндегі (ДБП) электрболат балқыту өндірісі процестерінде пайдалану қарастырылған. Әрбір процесс үшін биокөмірдің атқаратын функциялары және оның негізгі сипаттамаларына, соның ішінде реакциялық қабілеттілігіне, кеуектілігіне, тығыздығына және механикалық беріктігіне қойылатын талаптар жүйеленген. Кокстеу кезінде биокөмірдің үлесі, әдетте, шамамен 10 масс.% деңгейімен шектелетіні көрсетілген, өйткені оны қосу кокстың беріктігі мен реакциялық қабілеттілігіне кері әсер етеді. Темір кенін агломерациялау кезінде кокстық ұсақтығының 40–60 масс.%-ын биокөмірмен алмастыруға болады, ал домна пешіне үрлеу кезінде алмастыру дәрежесі

жану жағдайларына және фурмалық аймақта тұрақты температураны сақтау қажеттілігіне байланысты болады. Биокөмірді оттекті конвертерлер мен доғалы болат балкыту пештерінде пайдалану ең жоғары әлеуетке ие, мұнда ол қосымша энергия көзі, көміртектендіргіш және қожды көбіктендіруге арналған материал қызметін атқара алады. Биокөмірді өнеркәсіптік деңгейде қолданудың негізгі шектеулеріне оның қасиеттерінің тұрақсыздығы, төмен тығыздығы мен беріктігі, күл құрамының біркелкі болмауы және өздігінен қызуға бейімділігі жатады. Әрбір металлургиялық процесс үшін биокөмірге қойылатын арнайы талаптарды әзірлеу қажеттілігі туралы қорытынды жасалған.

Негізгі сөздер: көміртекті материалдар, металлургия, реакциялық қабілеттілік, биокөмір, биококкс, темір кенін агломерациялау, көміртектендіру, электр пештері.

Обзор основных направлений использования биоугля в производстве чугуна и стали

Л. Кешуш^{1*}, А. Коверя^{2,3}

¹K1-MET GmbH, Леобен, Австрия

²Национальный технический университет «Днепропетровская политехника», Днепр, Украина

³Технический университет Леобена, Леобен, Австрия

*Автор для корреспонденции: lina.kieush@k1-met.com

Аннотация. В данной статье обобщены основные направления применения биоугля в производстве чугуна и стали, а также требования к его свойствам как возобновляемой альтернативы ископаемым углеродсодержащим материалам. Рассмотрено использование биоугля в процессах коксования, агломерации железной руды, вдувания в доменную печь (ДП), кислородно-конвертерной плавки (ККП) и электросталеплавления в дуговой сталеплавильной печи (ДСП). Для каждого процесса систематизированы функции биоугля и требования к его основным характеристикам, включая реакционную способность, пористость, плотность и механическую прочность. Показано, что при коксовании доля биоугля, как правило, ограничивается приблизительно 10 мас%, поскольку его добавление отрицательно влияет на прочность и реакционную способность кокса. При агломерации железной руды биоуглём можно заменить 40-60 мас% коксовой мелочи, тогда как при вдувании в ДП степень замещения зависит от условий горения и необходимости поддержания стабильной температуры в фурменной зоне. Наибольшим потенциалом биоуголь обладает при использовании в кислородных конвертерах и ДСП, где он может выполнять функции дополнительного источника энергии, науглероживателя и материала для вспенивания шлака. К основным ограничениям промышленного применения биоугля относятся нестабильность его свойств, низкие плотность и прочность, неоднородный состав золы и склонность к самонагреванию. Сделан вывод о необходимости разработки специальных требований к биоуглю для каждого металлургического процесса.

Ключевые слова: углеродистые материалы, металлургия, реакционная способность, биоуголь, биококкс, спекание железной руды, науглероживание, электропечи.

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