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Review

Insight into the Potential Use of Biochar as a Substitute for Fossil Fuels in Energy-Intensive Industries on the Example of the Iron and Steel Industry

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Abstract

Actions related to reducing CO_2 emissions have led to the development of technologies using raw materials in the form of broadly understood biomass as CO_2-neutral fuels. There has been a rapid development of pyrolysis processes (carbonization, dry distillation) of various types of biomass toward the production of biochar for industrial applications. Particularly high hopes are associated with the use of biochar as a substitute for fossil fuel in energy-intensive sectors of the economy, especially the metallurgical and steel industries. This paper characterizes the current state and potential for biochar application, using the iron and steel industry as a case study. The analysis focuses primarily on the characteristics of biochar production and its industrial application potential. The characterization includes the diversity of biomass feedstocks, processing methods, and reactor types, the influence of operational parameters on biochar yield, as well as the properties and applications of biochar. As part of the analysis of biomass use potential in the iron and steel industry, the study reviews the current levels of coal substitution achieved at the laboratory scale and presents examples of biochar implementation in existing industrial facilities. In addition, key factors limiting the feasibility of coal substitution in the iron and steel industry are identified. The summary includes the main directions for further research aimed at increasing the use of biochar in industry.

Keywords: biochar; charcoal; biomass; fossil fuels; iron and steel industry; BF; EAF

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1. Introduction

Energy-intensive industry (EII) plays an important role in the context of greenhouse gas (GHG) emissions. Among the branches of the economy classified as EIIs are the production of iron and steel, cement, glass, non-ferrous metals (mainly aluminum), pulp and paper, chemical and petrochemical industry. In Tracking Clean Energy Progress 2023, a report by the International Energy Agency, there is a note indicating that the industrial sector was responsible for 9.0 Gt CO_2 emissions in 2022 [1]. The iron and steel industry had the largest share in emissions, its activity resulting in 2.62 Gt CO_2 emissions in the analyzed year. The next places in this ranking are taken by cement production (2.42 Gt CO_2), and then the chemical and petrochemical industry (1.33 Gt CO_2). The share of individual EIIs in greenhouse gas emissions from industry is presented in Figure 1.

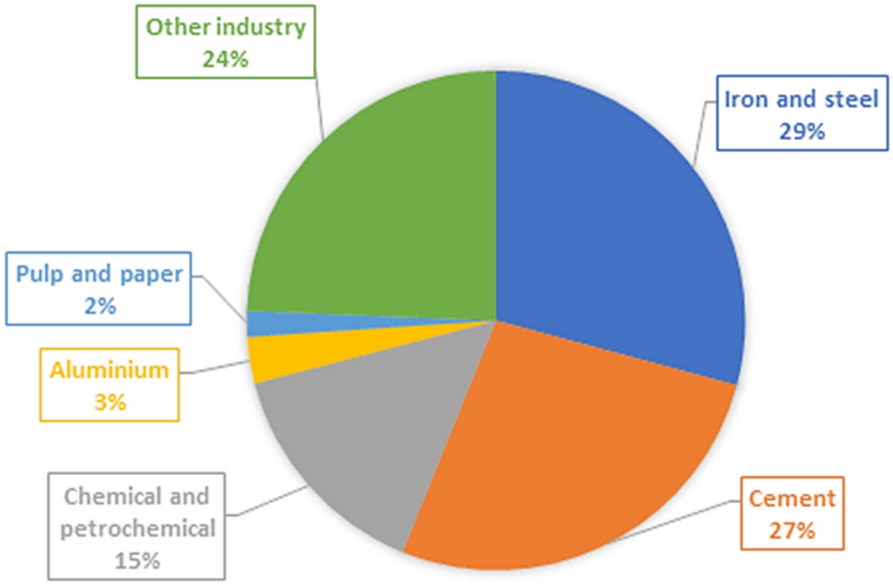

Figure 1. Global CO_2 emissions from industry in 2022.

As can be seen in Figure 1, iron and steel production in 2022 had the largest share in CO_2 emissions among all industrial sectors. This is primarily due to the significant demand for steel and iron, as well as the specificity of the production process itself, in which two sources of CO_2 emissions can be distinguished. Emissions come from both the production process itself—the use of coke as a reducing agent, and from the demand for fuel to provide high-temperature heat to the process [2]. In both cases, the basic fuel is coal, which covers about 75% of the demand for energy and feedstock of the steel and iron industry [1].

Decarbonization of EIIs is a technological and organizational challenge. It is a diverse group of technological processes. An individual approach will be required here, as well as investment costs related to the adaptation of existing installations or the development of new technological solutions or products [3–5]. Recently, recommendations have been developed for various types of energy-intensive installations, enabling a significant reduction of greenhouse gas emissions. In the case of the iron and steel industry, great hopes are associated especially with the implementation of the carbon capture, utilization, and storage (CCUS) system and the use of green hydrogen in the Direct Reduced Iron in Electric Arc Furnace (DRI-EAF) process [6,7]. According to Chan et al. [8], the solution using hydrogen in DRI allows for a 95% reduction of emissions in relation to the coal-based production process. Nevertheless, the proposed decarbonization solutions require high financial outlays, are currently not economically justified, or require significant adaptation of the technology. Therefore, it is assumed that decarbonization using the above methods will be implemented in the long term [2,6]. In the transition period, it is suggested to implement other solutions to reduce emissions, including replacing fossil fuels with biomass [7,9].

Biomass is considered a fuel with zero net greenhouse gas emissions. It is a broad group of raw materials of organic origin with diverse properties. Compared to fossil fuels, biomass is characterized by certain disadvantages. These include, among others, a large variety of raw materials, varying availability and price depending on the location or season, and worse fuel parameters than fossil fuels [3,10]. In the case of the iron and steel industry, raw biomass has little potential as a substitute for coal, which in production processes acts as a reducing agent and fuel [11]. Hence, it should be subjected to a thermal transformation process, most often by means of pyrolysis, possibly gasification, torrefaction, or hydrothermal carbonization, depending on the product we want to obtain. As a rule, we want to obtain the largest possible stream of a solid product characterized, among

others, by a high content of fixed carbon. The process that allows for obtaining such an effect is pyrolysis, and its product in the case of biomass raw material—biochar. It is the elemental carbon contained in charcoal that is an excellent reducer of iron oxides in iron ore and oxides of other metals. However, it should be noted that even the best types of biomass subjected to pyrolysis for the production of biochar usually do not allow obtaining a product with operating parameters allowing full substitution of fossil reducers [12].

In the introduction, it is necessary to refer to the nomenclature used in specialist literature and technical studies. Until recently, the term charcoal was mainly used in relation to a product of pyrolysis (also called dry distillation) of hard or soft wood and was not confused with anything else. Activities related to reducing CO_2 emissions have led to the development of technologies using raw materials in the form of broadly understood biomass, as fuels neutral in terms of CO_2 emissions. There has been a rapid development of pyrolysis processes of various types of biomass. In order to distinguish the solid products obtained in these processes from charcoal, the term biochar has begun to be used. Although there are currently no known standards organizing the issues of nomenclature regarding products of thermal conversion of biomass, it can be assumed that the conceptual scope of the term biochar is broader than the term charcoal. This means that all charcoal is biochar, but not all biochar can be charcoal.

2. Characteristics of Biochar Production Process

2.1. Diversity of Biomass Raw Materials

Biomass is a broad concept, encompassing biodegradable raw materials, which can be both products and wastes, including residues from forestry, agricultural production, etc. Therefore, this concept covers a very diverse group of materials, which can be classified depending on their origin. According to this approach, described among others by Jeguirim et al. [13], five categories of biomass raw materials have been defined:

- forest biomass,
- agricultural biomass (from plant cultivation),
- aquatic biomass,
- biomass from animal breeding,
- municipal and industrial biomass.

It should be noted here that the division of biomass into categories is conventional. Other approaches can also be found in the literature on the subject. Xie et al. [14] defined four groups of biomass used in the production of biochar, namely woody biomass, herbaceous biomass, animal and human waste, and biosolids sludge. The author of the analysis [15] divides biomass raw materials into six groups: woody, herbaceous and agricultural, aquatic, animal and human waste, contaminated biomass, and waste from industrial biomass, biomass mixtures. Mishra et al. [16] divide biomass raw materials into five types: energy crops, agro-industrial waste, agricultural waste, municipal solid waste, and forest waste.

Returning to the division mentioned [13], the category of forest biomass is connected with the production of charcoal (a special type of biochar), because it contains raw materials used in this production process. These are wood resources obtained directly from the forest for production purposes or constituting residues from wood processing processes. The category of agricultural biomass includes residues from agriculture and energy crops. These include straw, husks, pits, shells, and bagasse. Energy crops are crops intended for the production of biofuels, including mainly willow, poplar, and miscanthus. Aquatic biomass is considered a third-generation biofuel. It is classified primarily by origin, based on which marine and freshwater organisms are distinguished. Animal breeding waste, including manure and slurry, is a serious problem for industrialized countries. The last group of

raw materials with potential as input for the biochar production process is biodegradable municipal and industrial waste, which includes, for example, sewage sludge [1,17]. The properties of individual biomass raw materials may differ significantly, also within one biomass category. Table 1 lists exemplary biomass raw materials, one exemplary representative for each biomass category, along with their physicochemical properties.

Table 1. Physicochemical properties of selected biomass raw materials.

Properties	Unit	Biomass				
		Woody	**Agricultural**	**Aquatic**	**Animal Breeding**	**Industrial and Urban**
		Pine Sawdust [18]	**Sugarcane Straw [19]**	***Spirogyra* [20]**	**Cow Manure [21]**	**Sewage Sludge [22]**
Moisture	% mass	5.0	3.1	7.4	84.2	5.3
Fixed carbon	% mass	84.5	87.6	58.2	61.5	51.0
Volatile matters	% mass	15.4	3.2	7.2	26.4	12.5
Ash	% mass	0.1	9.2	34.5	12.1	36.5
C	% mass	49.5	41.9	30.9	48.1	31.8
H	% mass	7.1	5.9	4.0	6.1	4.4
N	% mass	0.5	0.5	4.2	1.7	4.9
S	% mass	-	-	0.4	0.2	1.7
O	% mass	42.8	41.7	28.5	31.7	20.6
Cl	% mass	-	-	0.3	-	0.2

High-quality biochar should be characterized by low moisture content at the level of 3–10%, low ash content—preferably not higher than 5%, and above all, high elemental carbon content (Cfix), which is most often in the range of 75–90% [23,24]. Among the above-mentioned biomass raw materials, it seems that the most valuable properties in terms of biochar production for the iron and steel industry are possessed by pine sawdust (woody biomass). The reason is the low moisture content (5%) and ash content (0.1%), and at the same time, a significant share of fixed carbon (84.5%). Due to the high fixed carbon content of sugarcane straw (agricultural biomass), this type of biomass looks equally promising in the context of producing biochar.

2.2. Methods of Converting Biomass to Biochar

Biomass conversion is carried out using the following methods: physical, thermochemical, and biochemical. In the first of the above-mentioned cases, the processes include crushing, drying, briquetting, and pelleting. As a result, solid fuel is obtained. Thermochemical methods include combustion, gasification, pyrolysis, and torrefaction. From the point of view of biochar production, including charcoal, the following processes should be distinguished: gasification, pyrolysis, and torrefaction. They lead to the creation of a solid product that can be used, among others, for energy purposes or in industry. This is evidenced primarily by the high content of fixed carbon. Biochemical processing of biomass is carried out by hydrolysis and alcohol and methane fermentation. A schematic summary of biomass processing methods is provided in Figure 2.

Biochar is produced both in the pyrolysis and gasification processes. It is worth noting, however, that due to the different conditions of both processes, their efficiency and properties are different. The pyrolysis process takes place at a temperature of 350–700 °C with an excess air ratio close to 0. In the pyrolysis process, it is possible to obtain up to approx. 35% by mass of solid product. Most often, this yield is in the range of 25–35% by mass. The biochar produced in this process is characterized by low moisture and ash content (<5% by mass) and a significant share of fixed carbon (75–90%).

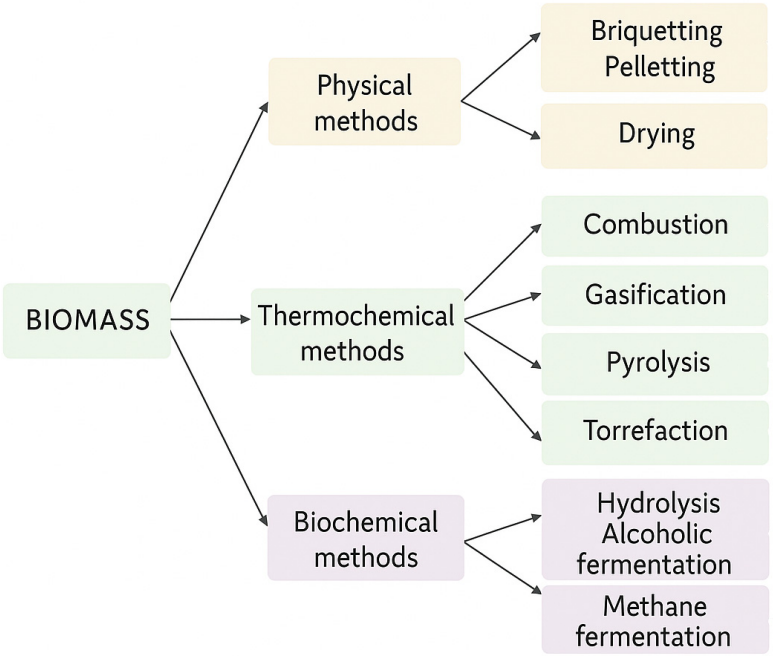

Figure 2. Methods of converting biomass.

Gasification is a process that takes place at higher temperatures (approx. 700–900 °C) with limited presence of oxygen (not allowing complete combustion of fuel). This process is primarily focused on significant yield of process gas, hence the yield of solid product during biomass conversion is usually 5–10% by mass. Biochar from gasification differs slightly from biochar from pyrolysis, which is more visible in the case of ash content and fixed carbon. Nevertheless, it is worth noting that these differences are generally not significant, and the existing possibilities of controlling process conditions can level them out or increase them to some extent.

Torrefied biomass is produced by thermal processing of biomass in an inert environment and under atmospheric pressure at relatively low temperatures, usually 200–350 °C. In such conditions, the three main components of biomass—hemicellulose, cellulose, and lignin—are degraded. However, it should be noted that the degree of decomposition for each of the components is different. This results from the range of decomposition temperatures for these components, which is as follows: hemicellulose—200–260 °C, cellulose—240–350 °C, lignin—280–500 °C. During this process, called torrefaction, about 30% of the initial mass of the raw material is reduced, which is caused primarily by the removal of moisture from it, but also by the partial release of volatile substances. Thus, solid (torrefied biomass), liquid, and gaseous products are obtained [25]. As a result of torrefaction, a homogeneous material is obtained with low moisture content and accumulated chemical energy, and also with better grinding properties compared to biomass, which allows for a reduction in energy consumption for its grinding, and thus it is possible to increase the share of biomass in the fuel stream in co-combustion processes. Torrefied product is biologically inert, which eliminates bacteriological threats and protects against fungi (safety of operation). It has hydrophobic properties (resistance to moisture), thanks to which storing biomass in this form is safe and free from the risk of environmental degradation. The yield of torrefied biomass is about 60–70% by mass [25,26].

Table 2 summarizes the most important characteristics of the analyzed thermal conversion processes—torrefaction, pyrolysis, and gasification.

Table 2. Characterisation of thermochemical biomass conversion processes.

Parameter	Unit	Torrefaction	Pyrolysis	Gasification
Process temperature	°C	200–350	350–700	700–900
Excess air ratio	-	~0	~0	<1
Fixed carbon	% mass	50–60	75–90	75–90
Solid product yield	% mass	60–70	25–35	5–10

When analyzing the data in Table 2, it is worth paying attention to the solid product yield from the process. The highest possible product yield with a high fixed carbon content is preferred. In the case of fixed carbon content, the type of biomass processed is of great importance. It can be seen that the solid product yield is at the highest level for torrefaction. However, a lower fixed carbon content in the torrefied product than in biochar should be expected. On average, it can be assumed that for high-quality biomass raw material, the fixed carbon content in the torrefied product is in the range of 50–60%, while for biochar from the pyrolysis process, this value is at the level of 75–90%. The difference is significant enough that higher fixed carbon content surpasses the lower yield. Especially if we take into account the criteria set for metallurgical reducers, which should be characterized by a high fixed carbon content of 75–90%. When comparing pyrolysis to gasification, it should be noted that the fixed carbon content in biochar from both processes is similar, while the biochar yield is significantly higher in the case of pyrolysis, which translates into a better assessment of this process in terms of selecting the optimal biochar production process.

2.3. Influence of Operating Parameters on a Biochar Production Process

The general rule for reducers used in the iron and steel industry is as follows: the more fixed carbon the reducer contains, the better efficiency the process will obtain [27]. Other operating parameters are also important, such as ash content, bulk density, and mechanical strength [14,23,24]. It is worth noting here the inconvenience associated with using biochar as a substitute. Coke as a reducer is generally repeatable in terms of parameters, while biomass is characterized by a fairly wide range of values of individual parameters. Therefore, the biochar produced may also present fluctuations in the parameter values, which may introduce uncertainty regarding the quality of the final product [28].

The pyrolysis process produces solid biochar, a mixture of condensable gases (water and volatile organic compounds) and a mixture of permanent gases (CO, CO_2, CH_4, H_2, and others). Variability of pyrolysis process parameters (temperature, heating rate, retention time of products) enables changing the composition and mass yield of three different final products [29]. Pyrolysis eliminates pathogens, while stabilizing organic matter and facilitating the recovery of valuable elements (including phosphorus and carbon) [30–32]. Several types of pyrolysis are distinguished based on the applied process conditions, such as temperature, heating rate, degree of fragmentation, or residence time at the final temperature. Assuming the heating rate as a criterion, pyrolysis can be generally classified as slow, fast, and flash [33]. A comparative summary is provided in Table 3.

As can be seen in Table 3, the rate of heating of biomass particles has a significant effect on the yield and composition of the pyrolysis products obtained. Rapid heating to a moderate temperature (400–600 °C) produces more volatile condensable products and thus more liquid product, while slower heating to this temperature allows for a higher yield of char. Of course, the rate of heating alone does not determine the properties of the pyrolysis product. The residence time of the product in the reactor is also very important. During slow heating, the slow or gradual removal of volatile products from the reactor allows for secondary reactions between the char particles and the volatile products, which can lead to the formation of a larger amount of char.

Table 3. Basic operating parameters of different types of pyrolysis.

Parameter	Unit	Pyrolysis		
		Slow	**Fast**	**Flash**
Temperature	°C	350–700	600–1000	800–1000
Heating rate	K/s	0.1–1	10–200	≥1000
Residence time	s	600–6000	0.5–5	<0.5
Particle size	mm	5–50	<1	dust
Solid product yield	% mass	30–35	15–25	10–20

The amount of biochar produced depends primarily on the pyrolysis temperature, heating rate, and residence time.

- Low temperatures result in the formation of a larger amount of solid product, while with the increase in pyrolysis temperature, the amount of biochar produced begins to decrease. Temperature also determines the porosity, specific surface area, and carbon content of the char [13,33].
- A high heating rate leads to the decomposition of volatile compounds and a lower yield of the solid fraction [34].
- A longer residence time reduces biochar yield by allowing further degradation of solids to volatile products and increases the level of secondary reactions [34,35].

Figure 3 shows, in general, the effect of pyrolysis parameters on the biochar yield.

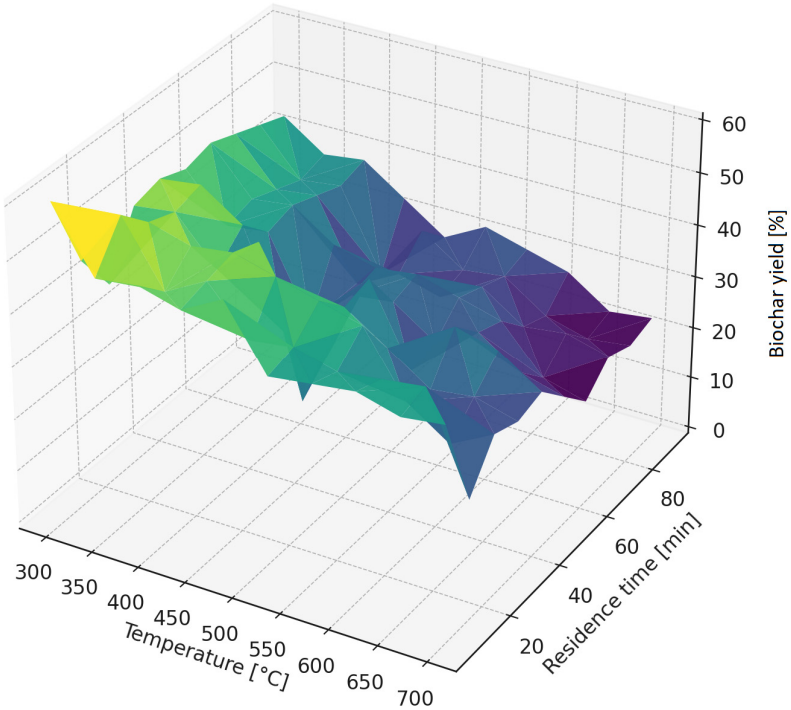

Figure 3. Effect of pyrolysis parameters on biochar yield.

2.4. Types of Reactors Used in Biochar Production

Biochar production installations equipped with carbonization reactors operate in the following modes: noncontinuous, semi-continuous, or continuous. Traditional charcoal production (a type of biochar) is generally based on noncontinuous production methods. These are usually very simple structures like brick furnaces. The efficiency of these devices is very diverse, and the final product obtained—charcoal—is often characterized by a unique quality. The average charcoal yield is usually in the range of 12–25% of the initial

raw material mass. Advanced design solutions allow for work automation, full process control, and reduced workload [36]. The most commonly used types of reactors in biomass pyrolysis include:

- Rotary reactor,
- Retort-type reactor,
- Combined reactor with a feeder.

The presented range of devices allows the conversion of various biomass raw materials towards the production of biochar.

2.4.1. Rotary Reactor

Rotary reactors (rotary kilns) belong to the most commonly used group of pyrolysis reactors, in which the material transport speed through the reactor is regulated by its rotational movement and the appropriate inclination angle (typically around 1–3°). In a typical reactor design, heat can be supplied either indirectly or directly. The inner surface of the reactor is often equipped with paddles or baffles to enhance mixing of the flowing feedstock. The front plates of the reactor contain inlets for fuel feeding and outlets for product discharge. Figure 4 shows a conceptual scheme of a rotary kiln reactor for biomass pyrolysis.

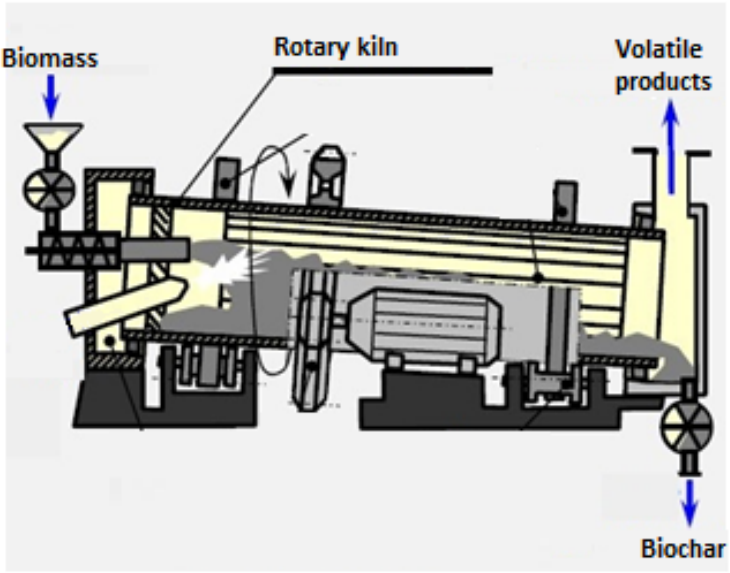

Figure 4. Scheme of rotary reactor for biomass pyrolysis.

A rotary kiln offers several operational advantages when used for biochar production through the pyrolysis of biomass. Due to the continuous character of performance, it is well-suited to large-scale production, providing a steady output without the downtime inherent in batch processes. The rotational motion promotes constant mixing of the biomass, which helps distribute heat more evenly and reduces the likelihood of unconverted material. Rotary kilns are also relatively tolerant of feedstock variability, handling a range of particle sizes, shapes, and moderate moisture levels without major process disruptions. This flexibility, combined with the fact that rotary kiln technology is already mature in industry, makes scaling up biochar production technically straightforward.

However, the rotary kiln design also comes with drawbacks in the context of biochar production. Performance characteristics can lead to breaking larger char pieces into fines, which can lower the market value of biochar. Its large external surface area makes heat loss more pronounced. Temperature control along the length of the kiln is less precise than in, for example, screw-type reactors. Energy demand is relatively and the mechanical

components—drive system, bearings, seals, and refractory lining—require periodic maintenance. Also, the capital investment for an industrial-scale rotary kiln can be significant.

2.4.2. Retort Type Reactor

The retort-type reactor typically consists of a vertical chamber loaded with feedstock for the pyrolysis process. Such a reactor can operate in a batch mode, where the retort chamber is filled with feedstock, sealed, and then subjected to pyrolysis by heating the bed until charcoal with desired properties is obtained; or in a continuous mode, where fresh feedstock is continuously supplied to the reactor and the product is simultaneously removed. Heat for the process is most commonly supplied in the form of hot flue gases, primarily from the combustion of pyrolysis gases, which flow through the reactor chamber in counter-current to the movement of the bed. Figure 5 shows a conceptual scheme of a retort-type reactor for biomass pyrolysis.

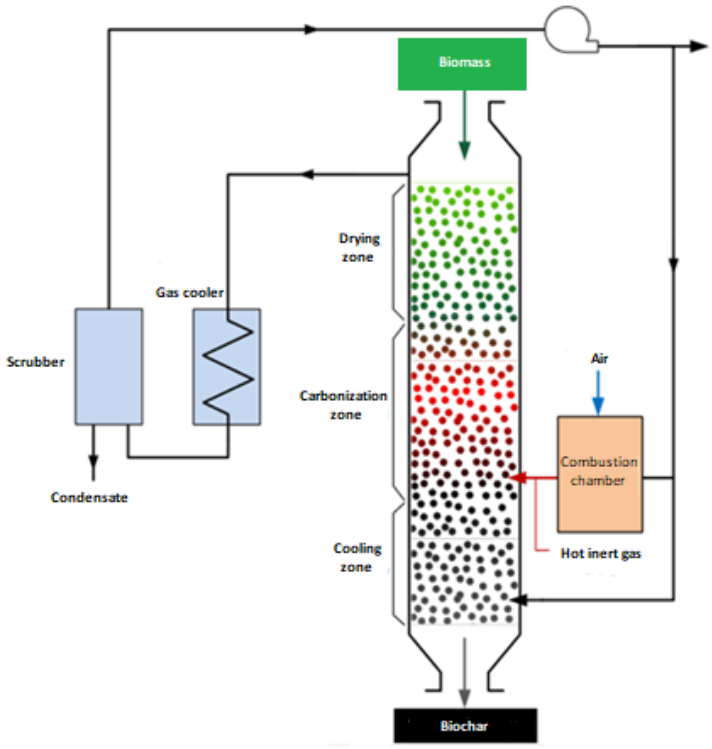

Figure 5. Scheme of retort-type reactor for biomass pyrolysis.

In biochar production, the retort-type reactor is valued for its simplicity and ability to produce biochar of satisfactory quality. The process that occurs in this type of reactor is slow, which allows for retaining a high fixed-carbon content in the biochar. Due to the lack of moving parts inside the reactor, mechanical wear is minimal, and maintenance needs are low. Retort systems are relatively inexpensive to construct and can be built from locally available materials.

Despite these strengths, retort-type reactors have limitations that make them less suitable for high-volume operations. In most cases, they are inherently batch systems, meaning each production cycle requires loading, heating, cooling, and unloading, which limits throughput. Retorts generally require uniform, well-prepared feedstock with low moisture to ensure proper carbonization. Labor demands can be high unless mechanized loading and unloading are added, and scaling up production usually means adding more units rather than simply enlarging a single one.

2.4.3. Combined Reactor with a Feeder

Another pyrolysis reactor design is the combined reactor with a feeder. This reactor features a stationary, tubular outer shell, while the transport and mixing of the material are achieved by the rotational movement of a screw or ribbon feeder inside. The reactor can operate in a horizontal configuration, although inclined reactor designs are also known. Heat is often supplied to the reactor via the outer shell using flowing flue gases, but electric heating solutions are also frequently employed. Figure 6 presents an example of a screw-feeder reactor for biomass pyrolysis.

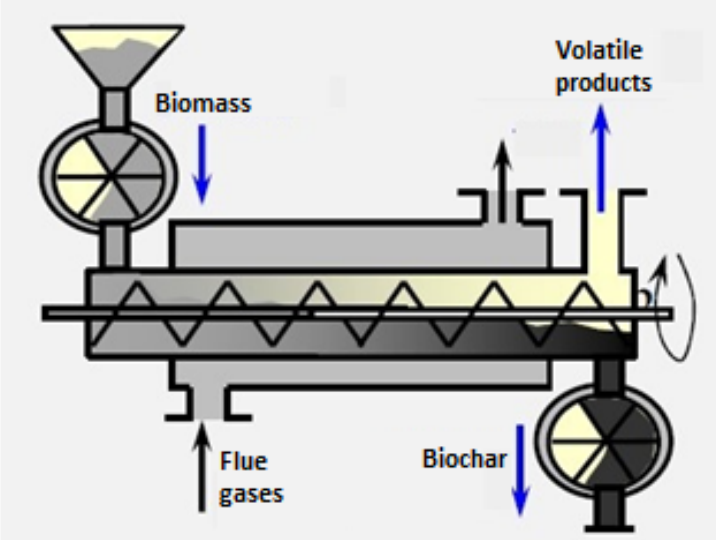

Figure 6. Scheme of reactor with a screw-feeder for biomass pyrolysis.

By adjusting the rotation speed of the screw, operators can precisely control the biomass residence time, allowing for consistent carbonization and repeatable biochar quality. Staged heating zones along the screw path enable a stable temperature profile and efficient use of thermal energy. The enclosed feeding system reduces oxygen ingress, lowering the risk of partial combustion. Screw-feeder reactors can be integrated with upstream dryers and grinders as well as downstream gas handling and heat recovery systems, making them versatile for modern, automated facilities.

The main drawbacks of reactors with a feeder are their mechanical complexity and sensitivity to feedstock properties. The screw, bearings, and seals must operate under high temperatures and in contact with abrasive biochar particles, which accelerates wear and raises maintenance costs. Some kinds of feedstocks, mainly fibrous, sticky, or oversized, can cause operational problems, so preprocessing—such as drying and grinding—is often necessary. The precision manufacturing and high-temperature materials required make this type of reactor more expensive to build than simple batch retorts. While they enable producing consistent biochar in a continuous process, their operational reliability depends heavily on matching the reactor design to the specific feedstock and production conditions.

2.5. Properties and Applications of Biochar

The properties of biochar can be very diverse. This results primarily from the characteristics of the biomass raw material, as well as from the parameters of the thermal biomass conversion process (including process temperature, residence time, heating rate) and from any refining activities.

Table 4, based on the research conducted by Liu et al. [37], presents the properties of exemplary biochars obtained in the pyrolysis process at a temperature of 500 °C. One representative was selected for each of the five previously specified biomass categories.

Table 4. Basic properties of biochars from selected biomass raw materials.

Type of Biomass	Temperature [°C]	Yield [%]	Fixed Carbon [% Mass]	Volatile Matters [% Mass]	Ash [% Mass]
Sawdust (woody)	500	28.3	72.0	17.5	9.9
Peanut shell (agricultural)	500	32.0	72.9	16.0	10.6
Waterweeds (aquatic)	500	58.4	3.8	32.4	63.5
Pig manure (animal breeding)	500	38.5	40.2	11.0	48.4
Wastepaper (industrial and urban)	500	36.6	16.4	30.0	53.5

In the context of the use of biochar in the iron and steel industry, attention should be paid primarily to the high content of fixed carbon, low content of moisture, volatile matter, and ash, as well as high flammability and susceptibility to grinding [38]. Another important aspect is the climate neutrality of biomass resulting from the previous absorption of CO_2 by the plant, which is equal to the emission of this gas at the stage of the production process [39].

Biochar is currently used mainly in the agricultural sector to improve soil quality. Moreover, its potential applications include the use in wastewater, soil, and gas purification processes, as a substitute for coal or coke in metallurgical processes, and for the production of electrodes [14,40]. Cement substitution in cement mortar has also been studied; however, biochar content higher than 5% is not recommended due to the deterioration of mechanical strength [24].

Biochar is characterized by adsorption properties, thanks to which it can be widely used in purification processes. Its effectiveness is studied especially in terms of wastewater and gas purification. In the case of wastewater, attention is paid to the possibility of removing, among others, heavy metals and organic compounds [41,42]. The effectiveness of adsorption of gaseous pollutants such as NO_X, SO_2, and H_2S has also been demonstrated [14,43]. Ripanda et al. [44] obtained biochar from jamun seed (*Syzygium cumini*) with high adsorption properties. This material is characterized by a peak surface area of 261.2 m^2/g, which ensures high adsorption efficiency, including small organic molecules. The authors of the study [45] used waste eucalyptus wood to produce biochar, which was then used for water purification with good results.

Biochar is also considered a soil fertilizing material, influencing the increase in yields, and counteracting desertification [46–48]. There are also reports indicating the possibility of using biochar in the energy storage and conversion sector, among others, in the production of supercapacitors [16]. The use of biochar in electrochemistry was also studied, indicating the benefits resulting from the use of this material as an electrode in microbiological fuel cells [14,49]. The metallurgical sector requires significant amounts of fossil fuels, which are used for energy purposes and as reducing agents. Biochar is characterized by properties similar to those of fossil raw materials. It has a relatively high calorific value, as well as a high content of fixed carbon and a low content of ash and volatile matter. Full substitution of fossil fuels is not currently possible, among others, due to lower mechanical strength. This applies especially to the use of biochar as a substitute for coke, which, in addition to the role of reducing agent and energy donor, also acts as a scaffold for the blast furnace charge.

3. Potential of Use of Biochar in the Iron and Steel Industry

3.1. Introduction

The demand for steel has increased significantly in recent years. In 2000, the global demand for this material was 189 Mg/year, while in 2022, this value increased to 1885 Mg/year [50]. Predictions of the demand for steel also indicate an upward trend. According to [38], the demand for steel in 2050 will increase 1.3-fold.

Iron and steel production is carried out in the vast majority of cases using two basic methods: the blast furnace—basic oxygen furnace (BF-BOF) and the electric arc furnace (EAF). In practice, the first of the above is used much more often. It is responsible for about 70% of global steel production [51]. The share of the second technological path in the market reaches about 25%. Other methods are also used to a small extent. The direct reduced iron (DRI) share is about 5%, while the LD converter is about 0.4%. The blast furnace process is also called the primary path [2]. The reason for this is the form of iron used in the process, namely, iron ore. The EAF process generally uses a secondary form of iron—recovered iron scrap.

Production requires significant amounts of substrates, which depend on the production method. In the case of the BF-BOF method, the production of 1 Mg of steel requires 1.4 Mg of iron ore, 800 kg of coal, 120 kg of recovered steel, and 300 kg of limestone [52]. In the case of the EAF method, the production of the same amount of steel requires approximately 1.04 Mg of scrap, 60 kg of oxygen, 30 kg of limestone, and several kilograms of natural gas and electrodes [53]. This does not include the fuel necessary to produce electricity, which is abundantly used in EAF.

The metallurgical industry uses a number of different production processes that have different criteria for the process substrates. As a rule, the material used in these processes should be characterized by a high content of fixed carbon, low content of volatile parts, mechanical strength, low reactivity, and density. However, the range of required values of these parameters is varied. The highest requirements for coke or biochar accompany the blast furnace technology. This is because the coke used in the process has a number of functions. It is an energy donor, a reducing agent, and should also ensure the permeability of the deposit and appropriate carburization of iron [54,55]. Other pyrometallurgical processes are characterized by less stringent requirements for the product. Hence, it is noted that in these processes, the possible substitution of fossil fuels using biochar is at a higher level than in the case of the blast furnace process [56–58].

In order to replace fossil fuel with biochar, it must be subjected to a thorough analysis in terms of its properties and their convergence or high similarity to the properties of coke. The key requirements for biochar are as follows:

- High fixed carbon content,
- Low volatile matter and ash content,
- High calorific value,
- High energy density,
- High mechanical strength,
- Low porosity [14].

Meeting the above quality requirements may be problematic for many types of biochar. Currently, charcoal is considered the best biochar for metallurgical processes, as it is characterized by high calorific value, high fixed carbon content, and low volatile matter content [56].

3.2. The Current State of Research and Industrial Usage of Biochar

The use of biochar in the steel and iron industry is currently not widespread globally. However, it can be noted that there are regional installations that successfully substitute fossil fuels. Industrial facilities in the iron and steel sector make only limited use of biochar as a substitute for coal. A review of industry reports has identified three regions where such a practice is being implemented: India, Brazil, and, more broadly, Europe. In the first case, a noteworthy example is a pilot project by Tata Steel at one of its plants, which, since 2023, has managed to reduce the use of 30,000 tons of fossil fuels in favor of biochar. This renewable fuel is injected into a blast furnace [59]. Another Indian producer, SAIL, also carried out trials in 2024 involving a 10–15% replacement of coke [60]. Brazil serves as an interesting example of the potential of biochar, due to its high availability in the country. This situation occurs, for example, in Brazil, where about 75% of the charcoal produced there is used in the domestic steel industry [56,61]. The main reason for this state of affairs is the availability of a large stream of wood raw material, with simultaneous shortages of coal. This country is the largest producer of charcoal in the world. In 2020, about 6.4 MMT of charcoal was produced there [61]. Availability also affects the economic aspect. In contrast to most other regions of the world, obtaining charcoal for iron and steel production is more economically advantageous here than purchasing fossil fuels. In Europe, various pilot projects are underway aimed at greening industrial production and reducing CO_2 emissions. These are being carried out in, among others, the United Kingdom, Sweden, Belgium, and Germany [62–64]. However, no full-scale use of biochar as a replacement for coal in the production process has been identified.

Gan et al. investigated the possibility of replacing coal in the iron ore sintering process. The process itself is responsible for 11% of CO_2 emissions in the entire steel production process. The authors found that coal substitution is possible up to a level of about 40% [65]. A reduction in the emission of gaseous pollutants such as CO_2 (by 23%), NO_X (by 31%), and SO_X (by 43%) was also achieved. The biomass raw material, which was the basis for the biochar used in the study, was fruit cores. The possibility of introducing biochars into the sintering process was also investigated by Niesler et al. [66]. In the course of the study, it was established that the level of possible substitution of fossil fuels was in the range of 10–30% mass, depending on the type of biochar [67]. There also exist reports indicating that the share of biochar depends largely on two factors, namely the content of fixed carbon and its grain size. Biochar with more favorable properties is the one with a fixed carbon content higher than 90% and a grain size in the range of 1–5 mm [67].

Meng et al. investigated the ability to reduce greenhouse gas emissions from steel production using biochar from two different sources—straw and wood. The results of the study aimed at finding an optimal substitution strategy indicated a higher efficiency of the wood-based reductant, which allowed for a reduction of 1.47 Mg CO_2/Mg crude steel, giving a reduction potential of about 67% [51].

The potential for fossil fuel substitution in the iron and steel industry also depends on the steel production method. In the case of the most commonly used blast furnace method, biochar can replace fossil fuels at the stage of coke production and iron ore sintering. In the EAF process, biochar can be used in the melting of scrap. In the case of the blast furnace method, coal can be supplied in two ways: in the form of coal dust by injection from the bottom of the furnace or in the form of coke from the top [67]. A greater potential for coal substitution by biochar occurs in the case of coal dust. Here, up to 100% of coal dust can be replaced, while coke substitution by biochar can only be partial. This is primarily due to the need for the coke substitute to also meet the role of input material skeleton. Coke, characterized by higher strength, ensures that this function is fulfilled, while biochar has lower mechanical strength and a higher content of volatile matter. Coke also provides

load-bearing strength, which ensures the permeability of the layer. It is indicated that the maximum substitution of coke with biochar for this process can be 20% [67]. In general, however, it is considered that biochar can replace up to 50% of coal in the iron and steel production process without reducing the quality of the final products [38].

3.3. Limiting Factors

Replacing some of the coal used in the iron and steel industry with biochar allows for substrate diversification and emission reductions without significant interference with the process line [27]. However, there are a few factors limiting the use of biochar in the steel and iron industries. Biochar, especially charcoal, usually has a high share of fixed carbon. The content of volatile matter in biochar is less favorable, often higher than in the case of coal or coke, ranging from 15 to 35% by mass [68,69]. This can result in an increase in the amount of flammable gases, faster use of the raw material in the process, and fluctuations in process parameters. There are more differences between fossil and biomass materials, primarily in the area of mechanical strength, porosity, and density. Biochar has less favorable properties in each of these areas, which can affect the costs of transportation and storage, higher reactivity, and lower product quality [68,69].

The selection of raw material for biochar production should be based on determining the optimal properties of the reducing agent in blast furnace processes. The differences in chemical and physical properties compared to fossil-based reducers can lead to a number of technical challenges associated with the use of bioreducers. Currently used reducers generally provide high mechanical stability and low gas reactivity. The fixed carbon content is expected to be in the range of 75–90%. Low moisture and volatile matter content is also important, preferably below 10%. Ash should also not constitute a significant share, preferably not exceeding 5% in the biochar. The content of ash components, such as alkali and alkaline earth metals, phosphorus, and sulfur, should be low to minimize catalytic reactions and slag formation. An upper limit for sulfur content (0.6%) and phosphorus (0.02%) has been determined. Table 5 lists suggested values of reducer parameters used in the iron and steel industry.

Table 5. Recommended properties of reducers in the iron and steel industry.

Parameter	Unit	Value
Moisture	% mass	<10
Fixed carbon	% mass	75–90
Volatile matters	% mass	<10
Ash	% mass	<5
Phosphorus	% mass	<0.02
Sulfur	% mass	<0.6
Grain size	mm	1–5

One of the factors limiting the potential use of biochar in energy-intensive industries, including the iron and steel industry, is the competition on the market for access to biomass raw materials. The basic use of arable land is for agricultural purposes. However, other sectors of the economy are also eager to use biomass [70]. Recently, a significant change can be seen in the energy sector of some regions of the world, which, striving for climate neutrality, have started to use biomass as a substitute for fossil fuels. Taking the above into account, it is worth testing less competitive biomass raw materials. This applies especially to waste biomass.

The economic aspect is also a significant barrier to the widespread use of biochar in the iron and steel industry. The costs of producing and distributing biochar in most cases exceed the costs of obtaining fossil fuels [71]. According to the technical and economic analysis of biochar production, the unit cost is in the range of 454–871 USD/Mg of biochar [72]. For comparison, the average cost of purchasing 1 Mg of coal used in the iron and steel industry is about 180 USD/Mg [51].

4. Summary

Recently, biomass raw materials for the production of biochar for industrial purposes, including for use in the iron and steel industry, have been increasingly considered. The idea behind these considerations is to replace the previously used fossil fuels with renewable raw materials. There are many technological solutions that enable the implementation of the biomass pyrolysis process for the production of biochar. The most commonly used include: a retort reactor, a rotary reactor, and a combined reactor with a feeder. Each of the mentioned types of reactor offers distinct advantages and limitations for biochar production, balancing factors like scale, feedstock flexibility, product quality, and operational complexity. Rotary kilns enable large-scale continuous processing but require high maintenance; retorts are simple and low-cost yet limited in throughput; and reactors with a feeder provide precise control and automation at the expense of mechanical complexity and higher costs. The choice of the reactor type should be considered primarily in terms of planned capacity, the predominant type of biomass raw material, and economic aspects.

Global steel demand has increased dramatically, rising from 189 Mt in 2000 to 1885 Mt in 2022, with forecasts predicting a 1.3-fold increase by 2050. Steel production mainly uses two methods: blast furnace-basic oxygen furnace (BF-BOF), responsible for about 70% of global output, and electric arc furnace (EAF), which accounts for around 25%. Fuels used in the iron and steel sector must have high fixed carbon (Cfix) content, low volatiles content, mechanical strength, and low reactivity. Currently, biochar use in steelmaking is limited but growing, with pilot projects in India, Brazil, and Europe demonstrating partial substitution of coal or coke with biochar. The effectiveness of substitution depends on the content of Cfix and particle size, with optimal biochar having over 90% Cfix and 1–5 mm grain size. According to the current state of the art, biochar could replace up to 50% of fossil fuels in iron and steel production without compromising product quality, offering a promising pathway for decarbonization.

While biochar has significant potential for decarbonizing the iron and steel industry, especially under pressure to meet climate targets, its widespread use faces barriers, primarily technical and economic. Three primary limiting factors constrain the substitution of fossil fuels with biochar in production processes: the inherent properties of biochar that restrict full substitution, the challenges of sustainably sourcing biomass feedstock, and the low economic viability of such substitution. Further research and development are needed to improve biochar properties, develop hybrid or mixed carbon sources, and adapt biochar use to compatible steelmaking methods.

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