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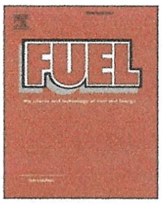

Review article

To what extent could biochar replace coal and coke in steel industries?

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ABSTRACT

The iron and steel making is considered among the biggest industries which run the world. This industry contributes around 20% of global industrial-sector energy consumption that is provided significantly by coal and coke. The fossil-based fuels are consumed largely for heat generation and reducing agents in steel production processes which leads to huge global CO_2 emissions. This matter encourages to find an effective, environmentally friendly, and sustainable substitute instead of coke and coal. Recently, biochar has received lots of consideration as a possible replace since the acceptable adaptation and comparable metallurgical properties to coal and coke. However, the biomass application in iron and steel making manufactures is currently limited and it endures strong competition with coal-based fuels. This paper investigates the key challenges affected on the steel production plant and the ability of biochar to overcome these difficulties. This work evaluates coal and coke substitution with biochar, focusing on metallurgical, technical and environmental aspects with the view of gate-to-gate analysis, from industry entry gate (input feedstocks that are coal or biochar) to exit gate (that is steel production). Moreover, the opportunities and obstacles of biochar performance in energy-intensive processes in steel production such as coke-making, sintering and blast furnace are discussed and finally, the main questions regarding the evaluation of these alternatives and their impacts on the system are answered.

1. Introduction

Burning different kinds of fossil-based resources releases huge amount of greenhouse gases to the atmosphere which intensifies climate change. In order to lessen climate change and avoid devastating consequences of global warming and climate problems, using fossil fuels as fuel need to be ceased [1–3]. In addition to the urgent requirement to reduce conventional energy resources for environmental issues, the war in Ukraine has much more strengthened effort to substitute a large quantity of conventional fuels with instant effects [4]. This action should be started from the industrial sector which accounts over 50 % of the energy consumption in the world and 36 % of global carbon emissions, making this sector very important for a switch to renewable resources and the realization of fossil-based fuels savings [5].

The iron and steel production manufacture includes among the most significant industries for each country that is well-known as the mother of all manufactures by helping to other secondary industries as well as to national and economic development [6]. Unlike many industries, iron and steel production have not much affected by the COVID-19 pandemic, confirming with annual production falling less than 1 % in 2020. Moreover, steel production increased to almost 1,950 million ton (Mt) in the world over 2021, a growth of 3.7 % from total amount of 1,880 Mt in 2020 [7]. Furthermore by 2050, steel utilization has been predicted to become greater 1.3 times higher than the current level to satisfy the needs of a growing population [8].

The global energy usage in iron and steel production has been approximated to be about 18 % of the yearly industrial energy consumption, it values about 9,885 Terawatt Hours (TWh) [9]. In addition, in order to make steel, manufactures need coking coal. Coal-based fuels are coupling to largely the world carbon emissions; the global coal consumption in iron and steel production has been estimated to be about 9,305 TWh in 2022 [10]. The fossil-based fuels are consumed largely for heat generation and reducing agents in steel production processes which leads to huge global CO_2 emissions. Relying on the International Energy Agency (IEA) statistics, ferrous metallurgy industry contains around 23 % of total global industrial CO_2 emissions [10]. Moreover, carbon emission through the iron and steel manufactures accounted about 2,600 million ton in 2019 that it was estimated to increase 2,700 million ton till 2050 if no sustainable development scenario is applied [11].

Steel production process can usually be categorized to four primary different methods like blast furnace/ basic oxygen furnace (BF-BOF), direct reduction/ electric arc furnace (DRI-EAF), smelting reduction/ basic oxygen furnace (SR-BOF) and melting of scarp in electric arc furnace (EAF) (Fig. 1). The blast furnace coupled with basic oxygen

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furnace has been presented as the most significant technology for steel making in the world which uses hugely coal and coke as both energy source and reduction agents. The BF-BOF method has assigned to itself approximately 70 % of steel production in worldwide. To make steel by using this method, iron ore is reduced by cokes/coals and is converted to carbon-rich pig iron in blast furnace (BF), then it is decarburized in basic oxygen furnace (BOF), and refined further to produce steel. For production of 1 ton crude steel by applying BF-BOF method, almost 1400 kg iron ore, 800 kg coal, 120 kg recycled steel, and 300 kg limestone are required [12,13]. The next significant way for iron making in the world is reprocessing and smelting of steel fragments in EAF method which contains about one-fourth of global steel manufacturing [14]. The DRI-EAF method utilizes mostly natural gas for energy carrier and reduction agent; it creates about 5 % of total steel in worldwide. The SR-BOF technology also consumes coal for iron ores reduction and provides only 0.4 % of global demand for steel [15]. Recently, the EAF option has grown a lot because of small scales, low capital and operational costs, high efficiency and productivity. As a mentioned example in literature [16,17] through this method, 1036 kg scrap, 28 kg limestone, 56 kg oxygen, 21 kg carbon, 3 kg electrodes and 4 kg natural gas are used for production of 1-ton crude steel. Although EAF consumes only low amount of coal as a raw material, the electricity applied is mostly generated by fossil-based power plants [12].

Although, the blast furnace produces major amount of total world steel requirement, producing 1-ton hot-rolled coil by applying this technology is attended by 1.8 ton CO_2 emission [13]. Consequently, the decrement of fossil fuel usage and GHG emissions need to be the prime concerns of iron and steel manufactures because of continuous increasing of energy costs as well as environmental problems. In recent decade, the iron and steel production processes have made significant amendments to mitigate the energy usage and gas emissions, however major reduction would be necessary to guarantee the future sustainability of this essential manufacture. Prediction of energy usage and carbon emission for years to come, determines that these two issues will increase continuously unless sustainable approaches are considered. Actually, an effective, environmentally friendly, and sustainable substitute instead of coke and coal would be so urgent.

The potential of biomass conversion products (e.g., syngas, bio-oil and biochar) with approach of industrial application in substitute of fossil fuels have been studied widely [19–22]. However, among all of them, the main product of renewable biomass in nature, biochar has received lots of consideration as a possible replace since the acceptable conformity, well ignitability and reduction capability [23–27]. Nevertheless, the biomass implementation in iron and steel making manufactures is still limited and need to compete strongly with coal-based fuels. In addition, the challenges regarding to biochar usage in iron and steel manufactures cover both technical and economic perspectives. Hence, the current work investigates thoroughly the important issues affected the steel production and the capability of biochar to overcome these difficulties. The opportunities and obstacles of biochar performance in energy-intensive processes in steel production e.g., coke-making, sintering and blast furnace are brought up and finally the following questions will be answered:

- To what extent could biochar replace coal and coke in steel industries?
- How this option could be evaluated? What indicators for this evaluation need to be studied?

2. Potential of biochar usage in iron and steel manufactures

Structure of the iron and steel making system by applying BF-BOF is shown in Fig. 2 [28]. The input coals are heated in an oxygen-free atmosphere until all volatile components in them evaporate. The material remaining is called coke. Conventional coke-making is carried out at a temperature around 1000 ℃ in heating walls in a coke oven battery. The produced coke is used in both blast furnace and sintering plant as reductant and a resource of thermal energy. It makes reduction of ore in the blast furnace to be converted to liquid metal and then refining of blast furnace hot metal to form steel. Sintering is a process for agglomeration of iron ore fines to be useful material in blast furnace. In this process, raw materials like iron ore fines, coke breeze, limestone and dolomite fines are blended with water to create an adhesive mixture, and then placed on a continuous, moving grate. A burner hood, at the beginning of the sinter ignites the coke in the mixture, after which the combustion is self-supporting and it makes adequate heat to lead surface melting and agglomeration of the mixture. The sinter ore is unloaded at the end of the sinter field, where it is crushed and screened. In the blast furnace the iron oxide is converted to iron in liquid state. This process needs reductant for iron oxide reduction and heat that the reduction reaction is accomplished and for the products of smelting are melted. The main source for fulfilling of both these requirements is done by coke, which contributes major part of cost of hot metal production. The general blast furnace is a vertical counter-current heat exchanger as well as a chemical reactor in which burden material charged from the top descend downward and the gasses generated at the tuyere level ascend upward. At the final stage, the basic oxygen furnace is applied for steel production. In this process, hot metal is added and oxygen is blown to the bath. Because of the exothermic reactions of oxidation, heat is generated and the temperatures increase. By using steel scrap as a coolant, the temperature can be controlled. Then, the steel is tapped by tilting the converter to the tapping side and alloying elements are added via chutes while metal is being tapped. The converter is also tilted to the charging side in order to remove the slag volumes [29,30].

In the integrated system for producing of iron and steel, the coke-making, sintering and blast furnace, are largely energy-consuming technologies that use higher than 75 % of entire energy consumption through the system. Approximately, all of carbon entered to the blast furnace is ineluctably transformed to carbon monoxide and carbon dioxide. Hence, BF process is taken into account the main participate to

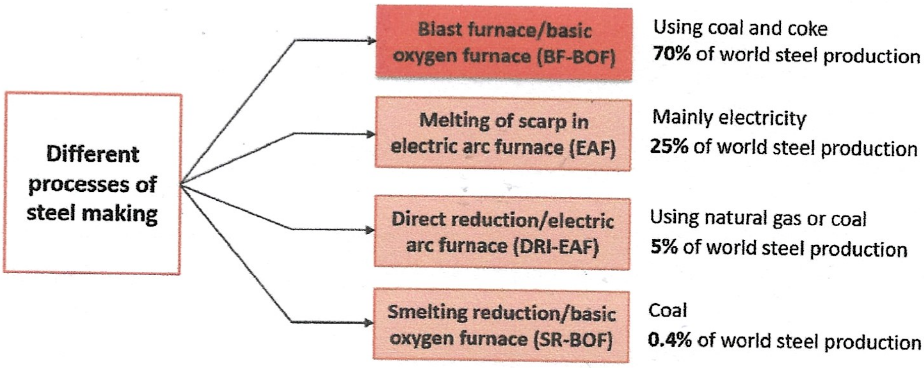

Fig. 1. Different types of iron and steel making industries [12,13,18].

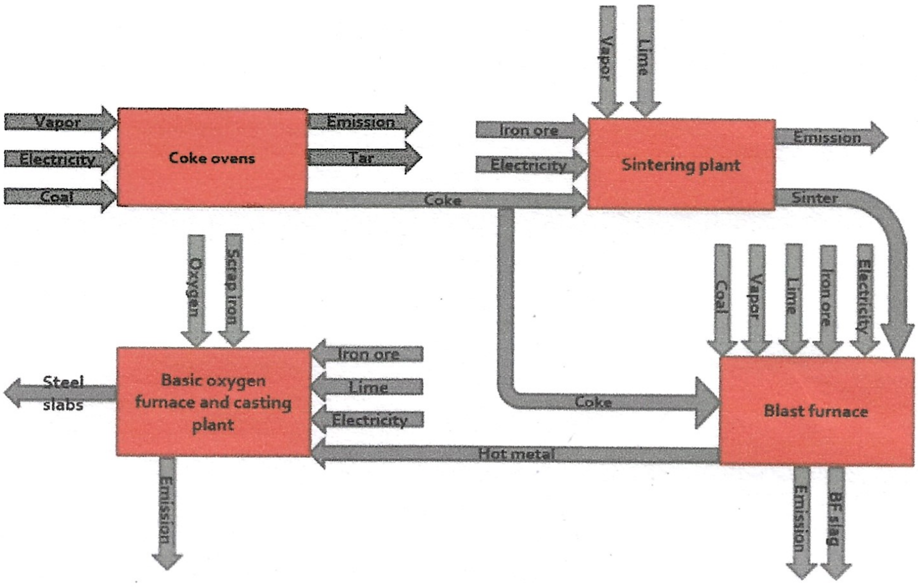

Fig. 2. Structure of the iron and steel making system by applying BF-BOF.

greenhouse gas (GHG) emission in iron and steel manufactures [12,31]. The energy usage in the coke-making, sintering and BF is around 6.54, 1.5 and 12.3 GJ per ton of product, respectively [32]. Moreover, the released CO_2 emission for these processes is around 0.79, 0.2 and 1.22 tCO2 per ton of product, respectively. Indeed, coke-making, sintering and BF contribute together almost 90 % of total amount of CO_2 emission in iron and steel industry. These high environmental impacts and high energy consumption have major contradiction with post-Kyoto requirements that need to find relatively instant and sustainable solutions for coal and coke reduction in energy-intensive technologies in steel industries.

By several researches [31,33,34] biochar has been selected as a promising solution for reducing agents and fuel to lessen the fossil fuel and CO_2 emissions in the steel industries. In fact, it has been confirmed that biochar has various potential to be used partially or completely in different parts of a steel industry. It can be replaced instead of coal and coke in coke-making, sintering and blast furnace plants but feasibility of this matter and maximum amount of replacement need to be found to have product with acceptable properties. Hence, in this paper the key challenges affected on the steel production and the ability of biochar to overcome these matters are studied. This work evaluates coal and coke substitution with biochar, focusing on metallurgical, technical and environmental aspects with the view of gate-to-gate analysis, from industry entry gate (i.e. input feedstocks) to exit gate (i.e. steel production) and processes for biochar production are not included. In the below sections usage potential of biochar in various parts of steel industry are investigated and discussed.

2.1. Comparison of physicochemical properties of biochar with coal and coke

The raw/unprocessed biomass fuels, originated from wood or any other organic material, cannot be utilized directly in substitute of conventional fossil-derived fuels consumed for steel making owing to their large moisture value, inadequate carbon content, and lower calorific value [35]. However, in view of general chemistry, the char derived from biomass has relatively complex physicochemical properties in comparison with raw biomass and its physicochemical properties are similar to low volatile coal or coke. Table 1 lists the physicochemical characteristics of various biochars derived from different biomass feedstocks compared to those of coke and coal consumed in ferrous metallurgy [36–41].

As it can be seen, two kinds of biochars produced by wood or crops biomass feedstocks have more volatile matter in comparison with these properties in coal and coke. They also include less ash content and impurities which is beneficial for iron-making. However, only wood biochars have acceptable range of fixed carbon in comparison with both coal and coke. On the other hand, fixed carbon involved in different

Table 1
Comparison of properties of various biochar types, coal, and coke.

Properties	**Biochar**					**Coke** [40]	**Coal** [41]
	Rubber wood char [37]	**Wood pellets** [37]	**Corn straw** [36]	**Lignin** [38]	**Walnut shell** [39]		
Proximate Analysis (wt.%)							
Moisture content	0.83	1.94	4.7	0.5	5.7	1.34	6
Volatile matter	9.08	11.06	13	41	35.7	10.3	41.5
Fixed carbon	87.49	83.04	72.9	58	56.6	88	39.6
Ash	2.6	3.96	14.1	0.5	1.8	0.4	12.9
Ultimate Analysis (wt.%)							
Carbon	87.17	87.32	91.53	75.3	56.57	87	80.7
Hydrogen	1.23	1.43	1.54	5.14	5.2	3.5	5.8
Nitrogen	0.4	0.33	0.7	0.97	1.5	1.1	1.2
Oxygen	11.2	10.9	6.16	18	36.6	0.5	8.7
Sulphur	–	–	–	–	–	7.9	3.6
Gross Calorific Value(MJ/kg)	30.38	31.07	27.6	30.18	25.54	27.2	20.6
Surface Area (m^2/g)	112.6	247.03	25	–	5.89	4.4	4.13
Bulk density (g/cm^3)	4.95	5.3	1.4	1.36	1.32	2.01	1.72

types of biochars (whether from wood or crops) satisfy the fixed carbon content in coal but not necessarily for coke. This explanation would be the same for calorific values. In fact, the higher carbon content in the fuel leads to the higher calorific values. In this way in terms of calorific value, chars produced by wood and woody biomass can be used in application of both coal and coke but other kinds of biochars need to be measured whether they want to be used instead of coke. For instance, biochars derived from lignin and corn straw show the admissible calorific value to be replaced with coke and coal. However, walnut shell biochar only can be applied instead of coal.

Regarding to surface area and bulk density, biochar, specially wood-based biochars have higher porosity and surface area, which these advantages cause the reactivity of biochar-based fuels would be much more than coke breeze reactivity. Moreover, it has a significant effect on the sintering process and its product quality. Indeed, with higher porosity, iron ore and coke are agglomerated together at lower temperature which leads to lower energy consumption and gas emission through the sintering process.

It is valuable to consider that the biochar properties are strongly dependent on its production method. The main technologies which are employed for biochar production are slow pyrolysis [42,43], fast pyrolysis [44,45], gasification [46–48], and hydrothermal carbonization [45,49], with various product yields and carbon contents. Among these technologies, the most common technology and the most successful one for high-yielding biochar production is slow pyrolysis [50]. Under the slow pyrolysis conditions, a biochar yield can be in the range of 25–50 % [49]. However, in some cases it has been reached to more than 70 %, depending on the feedstock properties, reactor type as well as the applied optimal operating conditions [51]. Through the slow pyrolysis, the temperature is less than 600℃, the residence time of the feedstock is long, the reactor operating at atmospheric pressure and low heating rates (0.01 to 2.0 ℃/s) [52,53]. These conditions allow all the volatile materials in the biomass to quit the solid char and nearly all the organic materials will be transformed to biochar as a carbon-rich material [54,55].

2.2. Potential for biochar in coke-making

Coke is well-known as a very significant and so costly feedstock for iron and steel production which is attributed with several key objectives. In term of thermal energy, it is consumed for heat production and around 80 % of heat demand is supplied by burning of carbon content in the coke and the rest is attained from the hot blast. As the chemical objective, coke is consumed for indirect and direct reduction of various oxides and hot metal carburizing. In view of physical objective, coke supports the burden descending, enhance the gas circulation and permeability through the bed, and adsorb dust [56]. So for all these purposes, coke could not be completely substituted in the coke ovens. However, partial blending biochar with coal to make bio-coke has been discussed in a few studied as a feasible option for reducing of coal consumption in coke-making process [31,57].

To produce bio-coke with sufficient quality, the maximum amount of biochar that can be mixed with coal is strongly depending on three indicators of fluidity and high temperature indices of coke which are CSR (e.g., coke strength after reaction) and CRI (e.g., coke reactivity indicator).

Fluidity, as one of the important indicators for high quality coke production, specifies the portion of coals-to-coal blends to make a plastic state. The coal fluidity is in span of 1 ddpm (dial division per minute) for noncoking coals to 5000 ddpm for hard coking coals. To produce coke with good quality, the coal blend needs fluidity in the window of 400–1000 ddpm [57,58]. The impact of adding of biochar on the coal blends fluidity has been studied for different kinds of biomass feedstocks. The results show that addition of charcoal usually decreases the fluidity in the coal-biochar blend and influences on the formation and stability of the coke matrix. This is mainly due to biochars have no tendency to alter to the plastic statue during the coke-making process. Guerrero and et al., [59] investigated the effect of lignin biochar addition on variation of fluidity in coking coals. The different charcoal fractions were added in amounts of 2, 5, 10, and 15 wt% to select high quality coking coals with a maximum fluidity. They found that growing the amount of charcoal in the mixture leads to a continuous inverse exponential reduction in fluidity. Indeed, the coal with a relatively high fluidity was very sensitive to minimum amount of biochar addition, losing about half of its fluidity when 5 wt% charcoal was added. So high amount of fluidity reduction was observed in the range of 51 to 66 wt% with the concentration of lignin biochar from 5 to 10 wt%. A similar trend was also noticed for sawdust biochar by Diez and et al., [60].

Two high temperature indicators of CSR and CRI are very important for the large modern blast furnaces. The modern blast furnaces require coke with CSR more than 60 % and CRI between 20 and 30 % to improve the permeability in the upper part of shaft and the combustion process in the raceway zone [13,61]. According to this matter, the high strength coke would be very needful for preventing the coke degradation and for keeping permeable the structure of the blast furnace. Ng and et al., [62] and Guerrero and et al., [59] studied on the partial substitution of coking coal with different biochars. They both reported that by adding of biochar to the coking coal, the CSR, CRI, and fluidity indices of the coke are declined and biochar has a negative effect on the quality of output coke. It can be explained that it is due to tough fusion of inert biochar compounds to the cell wall of the coal during cooking, that diminish the bonding of the produced coke compounds. Actually, in order to raise the biochar usage in the coke-making process, addition percentage and particle size were examined in most studies [63,64] and it was accomplished that it requires to keep adding of biochar in the range of 2–10 % to hinder its unfavorable impacts on the quality of the resulting coke. In fact, addition of 2 to 10 % biochar to the coal blend, reduces 1–5 % of CO_2 emission in the steel industry which it values 0.02–0.11 ton CO_2/ton crude steel [31]. Furthermore, by reducing the biochar‘s particle size, the CSR and CRI of the coke decline but fluidity slightly improve. Therefore, the optimal particle size range for biochar was found to be 2–4 mm.

2.3. Potential for biochar in sintering

Sintering process in the steel industry is operated to agglomerate the iron ore fines (typically less than 8 mm) via primary fusion of small mineral compounds. This process is carried out by the heat which is obtained from the coke breeze combustion and distributed uniformly through the mixture bed. In this way, the iron ore fines become larger, harder, and more permeable to be appropriate for high pressure and gas circulation in modern blast furnaces. It is worth to mention that the coke breeze is the significant fuel utilized in the sintering process and it is actually the smaller coke in size that is separated from those with larger sizes by screening after crushing [65].

Throughout the integrated steel plant, the sintering technology occupies 9–12 % of the overall energy consumption as well as 12 % of the total greenhouse gas emission [13]. Carbon dioxides are mostly released through the coke breeze burning and the decomposition of dolomite and limestone through the process. In addition to the carbon emission, this step is associated to other kinds of emissions such as sulphur oxides (SO_x) and nitrogen oxides (NO_x) [66]. Recently, employment of biochar as a renewable fuel for replacement with coke breeze has allocated much more attention since reduction in production costs and GHG emission. Several researchers have studied on the partial switching of coke breeze with biochar as an alternative fuel [67,68] and they showed that this function results in growing of CO and CO_2 values and decreasing of SO_x and NO_x values through the exit-gas (Fig. 3). For instance, when biochar addition increases from 0 % to 50 %, molar percent of CO and CO_2 increase from 1.3 % to 3 % and from 10 % to 12 %, respectively. The higher CO_x contents in the exit gas are related to more amount of charcoal is fed to the plant in comparison with the conventional coke

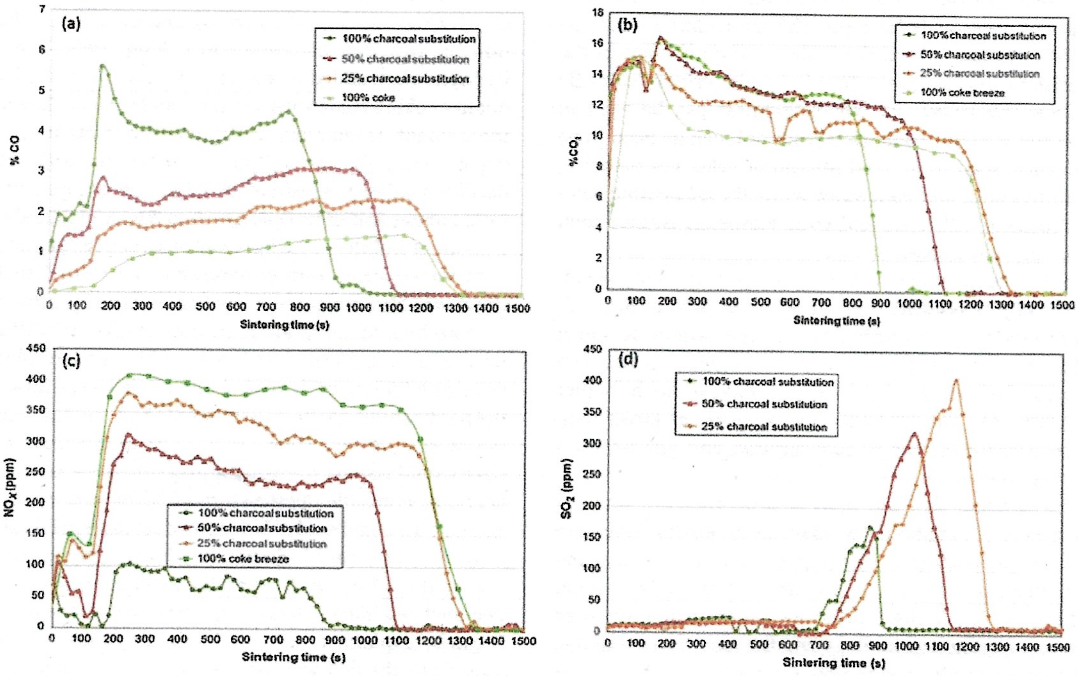

Fig. 3. Impacts of biochar usage instead of coke breeze on gas emission in sintering process [67].

breeze system. It happens because of more reactivity of biochar and also to attain the acceptable sinter quality. Furthermore, the less SO_x and NO_x contents within the exit-gas is connected to the less values of sulphur and nitrogen in biochar in contrast to coke breeze.

Biochar can absorb more water compared to the coke breeze along of much more surface area and more porosity. Indeed, the water saturation by biochar was examined to be about 48 % whereas it is 25 % for the coke breeze. This property is associated with negative impacts on the granulation of iron ore fines in the sintering process. In the case of biochar replacement, the granulation process consumes more water percent, about 8.5 %, in contrast to the conventional coke breeze system that needs about 7.1 % water. Hence, water quantity within the sintering system need to be modified to make the appropriate permeability through the bed and to reach the acceptable quality of the output product [12,69].

In order to investigate the effect of biochar usage instead of coke breeze on the performance of the sintering process, four important sinter indices need to be analyzed. These indices include sinter yield (%), product yield (%), tumbler index (%) and fuel consumption (kg/ton-sinter). Mousa et al. [69], have studied on various impacts of biochar addition in the sintering system from 0 % to 100 % by analyzing of the sinter indices (Fig. 4). Obviously, by increasing of biochar addition to the sintering process (especially after 25 % increase), the sinter yield is nearly fixed (about 78 %), the product yield and tumbler index are greatly reduced in contrast to the fuel consumption that is increased largely. According to several researches the adequate substitution of biochar for coke breeze is among 40 % to 60 % to have a sinter product with enough acceptable quality as well as to keep the product yield more than 80 % [63,66]. Actually, this range is dependent on the fixed carbon content in biochar and its size. In other words, biochar with fixed carbon more than 90 % and size in span of 1–5 mm, could be added around 60 % to the sintering plant to gain a product yield similar to that attained via coke breeze. Although, biochar usage within the sintering technology is not capable to reduce the GHG emissions, the net CO_2 emission in the steel industry has been estimated to decrease around 5 to 15 % since biomass feedstocks are considered as the carbon–neutral energy sources [70].

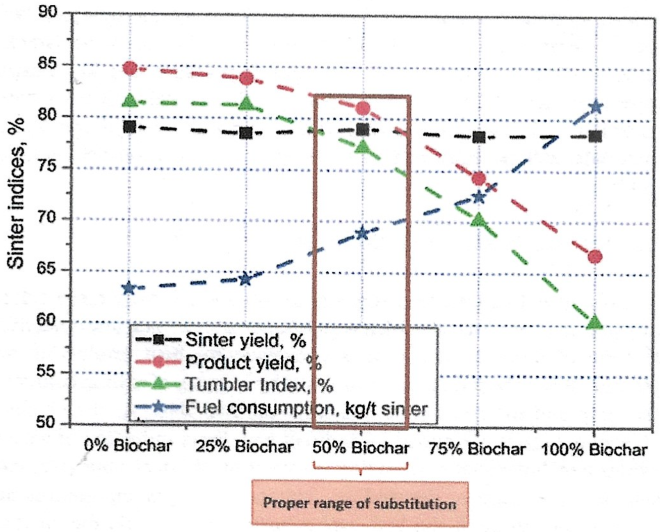

Fig. 4. Impacts of biochar addition on sinter indices [69].

2.4. Potential for biochar in blast furnace

The applied blast furnaces in the world are categorized in two groups of mini blast furnaces (MBF) and conventional large blast furnaces (LBF). MBFs (capacity in range of 50–350 m^3) are generally viewed as miniature versions of the LBFs (with capacity more than 4000 m^3). These furnaces are ideally suited for small scale operations. They are basically the forerunner to modern conventional last blast furnaces and hence they have operated for a longer period of time. MBFs are located in many countries but the majority of the MBFs are located in China, India, Brazil and Indonesia. Plant availability as well as the perfection achieved in this technology has made MBF an accepted route for iron making. Further, these days, most of the technologies of design, burdening and operation which have become the norm for today's modern large furnaces have also been adopted in MBFs [71].

In recent years, several alternative fuels for decreasing of pulverized coal (PC) and coke consumption in BF technology were introduced which among them, a number of researches investigated on biochar substitution for PC and coke in BF. Technically, it would be possible to add up to 200 kg biochar for 1 ton hot metal production [72,73]. In addition, there is no feasibility and technically limitation for replacement of 100 % coke with biochar in MBFs because the operational height and top pressure in MBFs are low which these help to biochar to meet the requirements for strength of burden. However in LBFs, specific characteristics of coke blend are required to create enough strength of burden and keep the bed permeable that these conditions only can be satisfied by maximum 20 % substitution [74]. Addition of 20 kg/tHM biochar with high fixed carbon to BF can lessen the coke usage nearly 30 kg/tHM because of reduction in reserve area temperature [75]. Addition of 50 to 100 % biochar to the coke blend, reduces 3–7 % of CO_2 emission in the steel industry which it values 0.08–0.16 ton CO_2/ton crude steel [31].

According to the modeling and experimental studies, pulverized coal injection (PCI) can be fully replaced with biochar in both types of mini and large blast furnaces [31,70,76,77]. Biochar has a great potential to be used instead of PCI and it was estimated that 166.7 kg biochar has this capability to substitute completely 155 kg pulverized coal for 1-ton hot metal production [77]. As a matter of fact 100 % substitution of PCI with biochar reduces 19–25 % of CO_2 emission in the steel plant, accounting for 0.41–0.55 ton CO_2/ton crude steel [31]. Alongside the environmental advantageous, biochar usage instead of PCI brings about smaller slag amount since it contains lower impurity and ash in comparison with PCI [78].

3. Conclusions

The practical and feasible substitution of coal-based fuels with renewable biochar can be introduced as an option for CO_2 reduction in the steel industry. This study has evaluated the recent researches which have been accomplished on the biochar application in the steel industry. The challenges and opportunities for biochar usage in the main energy-intensive processes in steel production (i.e., coke-making, sintering and blast furnace) have been studied and finally this work can be concluded by summarizing the following points:

In view of physicochemical properties, the biochars derived from wood and woody biomass can meet the requirements for coal and coke substitution. However, other types of biochars need to be examined for fixed carbon content (>80 %) and calorific value (>27 MJ/kg) whether they want to be used instead of coke.

In coke-making process, it is possible to blend biochar with coal to make bio-coke but it is necessary to keep biochar addition in the range of 2–10 % to hinder its unfavorable impacts on the quality of the output bio-coke. Adding this range biochar to the coal blend, reduces 1–5 % of CO_2 emission in the steel industry which it values 0.02–0.11 ton CO_2/ton crude steel.

In sintering process, the adequate substitution of biochar for coke breeze is between 40 % and 60 % to have the good quality sinter product as well as to keep the product yield more than 80 %. Actually, this values are strongly depending on the fixed carbon content in biochar and its size range. In other words, biochar with fixed carbon more than 90 % and size in the span of 1–5 mm, could be added till 60 % to the sintering plant to gain a product yield similar to that attained via coke breeze.

In blast furnace technology, biochar has the highest potential to be substituted completely with pulverized coal injection and partially replacement with coke in large blast furnaces. Indeed, the specific properties of coke blend is required to create enough strength of burden and keep the bed permeable that this condition only can be satisfied by maximum 20 % substitution. Biochar has a great potential to be used instead of PCI and the maximum injection rate of biochar was in the range of 200–220 kg/tHM, showing the potential to reduce the CO2 emissions by 25 %.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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