Metallurgical Coke Production with Biomass Additives. Part 2. Production and Characterization of Laboratory Biocokes

Andrii Koveria, Lina Kieush, Pavlo Saik, and Vasyl Lozynskyi

1 Introduction

The development of technological processes in the modern world follows the path of reducing the environmental impact, using renewable sources of energy and raw materials while simultaneously obtaining products of the required quality [1–4].

Based on the results of the annual UN conferences on climate change [5], further commitments are planned to reduce greenhouse gas emissions globally [6, 7]. This requires a significant modernization of production to ensure the environmental sustainability of the industrial development of the metallurgy [8–10].

In the next five years, a significant proportion of the world's existing integrated steel plants will reach the 60-year age limit and be decommissioned. In addition, it is expected that in 2040–2060 blast furnaces (BF) with a total production of about 200 million tons per year will be decommissioned before reaching final depreciation. There will probably be no need to build new blast furnaces.

Ensuring the sustainable development of metallurgy, particularly in light of future restrictions on CO_2 emissions, requires the modernization of the industry with the introduction of innovative technologies and the improvement of the existing ones [11–14].

Coke production technology greatly impacts the natural environment due to using fossil coal. The primary consumer of coke is blast furnace production, the technology of which imposes specific requirements on the quality of the coke [15–17]. To meet the high requirements, which are constantly increasing, it is necessary to use raw

---

A. Koveria (✉)
Department of Chemistry, Dnipro University of Technology, Dnipro, Ukraine
e-mail: koverya.A.S@nmu.one

L. Kieush · P. Saik · V. Lozynskyi
Department of Mining Engineering and Education, Dnipro University of Technology, Dnipro, Ukraine

S. Boichenko et al. (eds.), *Modern Technologies in Energy and Transport*, Studies in Systems, Decision and Control 510, https://doi.org/10.1007/978-3-031-44351-0_15

materials with suitable initial characteristics (according to proximate analysis, coking ability, and coarseness) to produce coke.

Along with the blast furnace industry, which uses up to about 70% of the coke produced, several other industries use coke and have related requirements. For example, for ferroalloy production, using more reactive coke with a grain size of 10–25 mm is desirable. For the sintering of ores, coke fines (<10 mm) are needed, along with high reactivity. In foundry production, coke should be coarse and low-reactive [15]. Non-blast furnace consumers need coke for high-temperature reactions. The function of carbon materials in these processes is to provide the necessary temperature for reactions and carbon transfer for carbonization.

As an alternative to fossil fuels, renewable energy sources from organic raw materials are increasingly used [17–23]. The most important of them is the vegetable raw material formed in photosynthesis. Biomass is the product of converting solar energy into chemical energy. Plant biomass is a valuable renewable chemical raw material from which unique compounds and fossil fuel substitute products can be obtained.

It is known that charcoal was widely used in the production of cast iron until the middle of the twentieth century [24]. Charcoal is used as the main fuel and reducing agent in small blast furnaces in Brazil [25–27]. However, charcoal is mainly used in the blast furnace process for injection into the BF via the tuyeres [25, 28–31], as well as the carbon iron ore composite [32] and steel recarburazer [33]. At the same time, Brazil is one of the leading countries in using charcoal for steel production [34].

The advantages of using charcoal in the BF process, as opposed to coal coke, are low ash, sulfur, and high porosity. As an injecting component, charcoal has high reactivity and low mechanical strength. However, the use of charcoal for feeding into BF is ineffective precisely because of these features of mechanical and chemical properties.

At the current state of industry development, biomass is important as a renewable source of raw materials that do not increase the amount of CO_2 in the atmosphere. Biomass, as a substitute for fossil fuels, is actively used to produce biofuels [35–39], in the energy [38, 40–42], obtaining nanomaterials [43–47], bioplastics [48–51], as an effective adsorbent [52–55], as well as fertilizer [56–58].

Over the past couple of decades, the issue of using biomass and its products in the metallurgical process, namely in the BF process [59–63], sintering ores [64–71], electrical arc furnace (EAF) to enable carburizing and slag foaming [72, 73], submerged arc furnace (SAF) [74–76], reduction of iron [77–79] has been actively studied. At the same time, the amount of replacing the use of reducing raw materials instead of the conventional one depends on the type of process and the properties of biomaterials. Studies demonstrate that it is possible to increase the share of biomass use and its efficiency through the use of biocoke [80–83].

Co-pyrolysis of biomass and coal can be considered as one of the possible ways of controlling the thermochemical conversion of coal and the formation of molecular structure and physical and chemical properties of the solid residues. However, for the effective use of biomass as a fuel and raw material for chemical products, it should be considered that biomass from different sources has different properties [84].

Studies on the effect of biomass additives on the caking process and coke properties show that a minor proportion of some biomaterials (up to 3 wt.%) in the mixture does not significantly affect the caking of coals [85, 86]. When studying the behavior of the removal of volatile matters from mixtures of biomass and coal, some authors found that no interaction occurs, and the yield of pyrolysis products is associated only with the amount of biomass and coal in the blend [87–90]. Other authors have observed interactions between coal and biomass in co-combustion [91] and co-pyrolysis of biomass and brown coal [92].

When studying the issue of using biomass for co-processing with coal, it is necessary to have a clear, theoretically substantiated, confirmed-by-practice understanding of the processes of thermal destruction of the mixture with the formation of a solid residue and chemical products (tar, gas). Analysis of publications on the co-pyrolysis of coal and biomass [93, 94] highlights the main patterns of ongoing processes, depending on the temperature stage of processing (Table 1). At the same time, lignocellulosic biomass is considered a natural polymer consisting of hemicellulose, cellulose, and lignin, the thermal destruction of which has its characteristics [95].

Thus, the relevance of the use of biomass in metallurgy, as well as a small number of studies on the production and analysis of biocokes, formed the main aim of the chapter is to establish the effect of biomass additives on the yield and quality of biocokes. Co-pyrolysis of coal blend and various types of biomass was carried out via a laboratory shaft furnace with different portions of biomass additives (up to 45 wt.%) and their forms (pellets and chips). The supplementary aim considered in this chapter is to analyze the influence of the type of biomass, its quantity, and form on the technical and physical–mechanical properties of biocokes and quality analysis of biocoke for compliance with the requirements of metallurgical processes.

2 Materials and Methods

Materials

Table 2 shows the characteristics of the coals that were used to prepare the coal blend. Coals are characterized by high sulfur content, typical for Ukrainian caking coals. It should be noted that the thickness of the blend's plastic layer (y, mm) was 12 mm, which is 2 mm less than conventional coal blends used for industrial coking. The indicators of the proximate analysis of coals were determined according to ASTM D3172-13 [96] and plastometric values according to [97–99].

Indicators of reflectance of vitrinite, vitrinite reflectogram, and petrographic composition of the coal used in the research are given in Table 3. The indicators were determined according to [100–102].

The average vitrinite reflectance (R_o) is 1.01%, while the values corresponding to industrial charges with good coking characteristics are 1.1–1.2% [97].

Table 1 Main processes that occur during the pyrolysis of biomass and hard coal

Temperature range, °C	Component	Description	Main processes
up to 105 °C	Hemicellulose	Moisture removal. The duration of the stage is determined by the moisture content and the weight of the charge	Dehydration. Evaporation of water occurs in a narrow range of about 100 °C This stage determines the subsequent course of the pyrolysis process in terms of the temperature field formation of the charge
	Cellulose		
	Lignin		
	Hard Coal		
105–270 °C	Hemicellulose	Drying and start of decomposition at temperatures of about 200 °C	Removal of adsorbed moisture Formed mainly CO, CO_2, and acetic acid
	Cellulose	Drying and decomposition start early, even at 240 °C	
	Lignin	Drying and minor decomposition start early, even at 260 °C	
	Hard Coal	Removal of colloidal moisture and occluded gases (CO_2, CO). Drying	Removal of adsorbed moisture Pre-plastic state
270–350 °C	Hemicellulose	Active decomposition	Isolation of combustible gases CO, H_2, CH_4, CO_2, acetic acid, methanol, acetone, etc., and tar
	Cellulose		
	Lignin	Beginning of active decomposition	
	Hard Coal	Softening of coal with the beginning of the formation of coal plastic layer	Pre-plastic state
350–420 °C	Hemicellulose	Completion of decomposition	The release of combustible gases CO, H_2, and CH_4, along with CO_2, acetic acid, methanol, acetone, etc., and tar
	Cellulose		
	Lignin	Active decomposition	
	Hard Coal	Plastic state	The main process of pyrolysis. Active physical and chemical processes with the participation of coal plastic layer and the release of volatiles
420–500 °C	Hemicellulose	–	Formation of charcoal
	Cellulose	–	

(continued)

Table 1 (continued)

Temperature range, °C	Component	Description	Main processes
	Lignin	Completion of active decomposition	
	Hard Coal	End of the plastic state	Beginning of resolidification after the plastic layer formation stage. Intensive formation of volatile substances and tar
500–550 °C	Hemicellulose	–	Formation of charcoal Completion of carbonization of charcoal
	Cellulose	–	
	Lignin	Further decomposition	
	Hard Coal	Semi-coke formation and its further decomposition. The transformation of semi-coke into medium-temperature coke occurs above 700 °C, and after 950 °C, the formation of high-temperature coke	Accompanied by shrinkage processes and the release of volatile matter, mainly hydrogen, and hydrocarbons

Table 2 Characteristics of coals and blend

Coal type	Amount within the blend, %	Proximate analysis, %				Plastometric indicators, mm	
		W^a	A^d	V^{daf}	$S^d{}_t$	y	x
Coal A	30	1.5	11.3	37.6	1.92	12	32
Coal B	30	1.6	7.6	34.1	2.38	18	10
Coal C	30	1.7	9.5	22.3	1.67	16	11
Coal D	10	2.0	6.8	17.6	1.51	<6	20
Blend	100	1.6	9.2	30.0	1.37	12	21

As is known, coals' size strongly influences their thermal processing processes [103–105]. To exclude the influence of coal particles of different distributions on the quality of coke, a stable granulometric composition of coal of various types was taken, which was maintained during the preparation of coal blends. Firstly, coal of a specific granulometric composition was prepared, and afterward, it was mixed to the particle size distribution according to Table 4.

Wood, sunflower husks, and straw were used as biomass additives in the form of pellets with a diameter of 8 mm and a length of 4 to 12 mm. Additionally, for comparison, when coking the blend, wood chips were used as an additive. The biomass additives' properties are summarised in Table 5.

Table 3 Average reflectance of vitrinite, petrographic composition, and reflectogram of vitrinite of coal

Coal type	R_o, %	Vt, %	Sv %	I, %	L %	$\sum$OK, %	Reflectogram of vitrinite, %						
							<0.5	0.5–0.64	0.65–0.89	0.9–1.19	1.2–1.39	1.4–1.69	1.7– > 2.2
Coal A	0.75	71	1	20	8	21		3	89	8			
Coal B	0.93	87	1	9	3	10		14	34	31	21		
Coal C	1.18	93	1	6	–	7			1	65	16	18	
Coal D	1.52	88	2	10	–	12				5	10	65	20
Blend	1.01	84	1	12	3	13		5	37	32	12	12	2

Table 4 Particles size distribution of coals

Coal type	Content of sizes, %				
	10–6 mm	6–3 mm	3–1.5 mm	1.5–0.5 mm	<0.5 mm
Coal A	4	10	31	30	25
Coal B	4	22	30	24	20
Coal C	3	17	24	33	23
Coal D	2	8	27	32	31
Blend	3.5	15.5	28.2	29.3	23.5

Table 5 Characteristics of additive properties, wt.%

Type of additive	Moisture (W_t^r)	Volatile matters (V^r)	Total sulfur content (S_t^d)	Ash (A^r)
Wood	9.4	81.3	0.01	1.0
Sunflower husks	9.6	75.7	0.01	2.6
Straw	4.7	75.0	0.01	5.4

Methods

Laboratory Coking

Coking was carried out in a laboratory shaft furnace [80] at 800 °C. The load was 1 kg, and after being charged in a retort, it was placed into a heated furnace. After finishing coking, the retort with the obtained coke was taken out and left to cool to room temperature. The coking time was 80 min.

Yield of Coke

After naturally cooling to room temperature, the obtained cokes were subjected to the analysis of the yield, %. The yield was calculated using Eq. 1.

$$Yield = \mathrm{B} \times 100/A,\ \% \tag{1}$$

where A is the initial mass of the blend, g; B is the mass of coke/biocoke after coking, g.

Particle Size Distribution of Coke

Further, the resulting cokes were sieved into sizes > 40, 40–25, 25–10, and < 10 mm according to ASTM D293/D293M-18 [106].

Structural Strength

To determine the structural strength, coke and biocoke samples of 6–3 mm were prepared. Then samples were charged into two special steel cylinders according to [107]. Likewise, five steel balls were placed in the cylinders. These two cylinders were set through screws in the cross-to-cross position in brackets, which were put on a shaft rotating with 0.417 s^{-1} (25 rpm). During the tests, the cylinders performed 1000 revolutions, after which the contents of each cylinder were poured separately on a sieve with a mesh of 3 mm and 1 mm. Coke or biocokes were sieved to separate into 3–1 mm and 1–0 mm fractions. The yield of more than 1 mm from the initial weight in percent characterizes the structural strength.

Abrasive Hardness

The abrasive hardness was determined by the abrasion of an aluminium plate against coke or biocoke powder and the evaluation of its mass loss. 4–5 g of samples of less than 0.5 mm in size was filled on an aluminum plate. A stamp was placed on top of the samples of coke or biocoke, which were loaded so that a pressure of 0.25 MPa was obtained. During the rotation of the rotor (500 rev.), the samples abraded the aluminum plate. The weight loss of the aluminium plate during the test run (in milligrams) was taken as the value of the abrasive hardness. Five tests were conducted for each sample.

Electrical Resistivity

The electrical resistivity measurement was carried out according to [108]. The method aims to determine the electrical resistivity of the particles with a size < 2 mm placed in the cylinder between two stainless steel plungers under a pressure of 3 MPa. The resistivity measured using a four-point mode is advantageous because it allows measuring resistivity close to the actual resistivity of the sample [109].

3 Results and Discussions

The characteristics of biocokes obtained from coking are summarized in Table 6. The yield of laboratory biocokes decreases with an increase in biomass additive, which has a higher yield of volatile matter than coal. The ash content of biocokes decreases due to the lower content of mineral components in the biomass. There is also a decrease in sulfur content since biomass additives practically do not add it to the mixture.

The yield of volatile matters of biocokes is determined by the level of readiness and varies from 0.8 wt.% to 2.5 wt.%. However, there is a tendency that with an increase in the proportion of biomass addition, the yield of volatile matters of the obtained biocokes increases.

The effect of biomass additives on the physical and mechanical properties of biocokes is more significant. The amount of 1 wt.% and 3 wt.% pellets of three types of biomass, as well as 5 wt.% wood pellets do not cause a deterioration in the particles size distribution of biocokes compared to the reference coke. At the same time, the use of wood chips has a more noticeable effect on the size of biocokes in the direction of a decrease in large sizes (>25 mm) and an increase in small ones (<10 mm). In general, with an increase in the proportion of the additive, there is a trend towards a decrease in the yield of large sizes and a corresponding increase in small ones.

Adding up to 3 wt.% of sunflower husks and straw pellets has a positive effect on structural strength. The additives of wood pellets and wood chips reduce the structural strength. At the same time, the negative effect of using chips is more pronounced than for pellets (Fig. 1). Similar dependences are observed when studying the impact of biomass additives on the abrasive hardness of the obtained biocokes (Fig. 2).

Thus, the addition of sunflower husk pellets up to 5 wt.% and straw up to 3 wt.% led to an increase in abrasive hardness, as well as the use of wood chips up to 3 wt.%. At the same time, adding 3 wt.% chips significantly increases the abrasive hardness index, although adding wood pellets decreases this index. This can be because fine coke (<0.5 mm) is used to study abrasive hardness. Therefore the value of the index depends to a greater extent on the degree of biocoke readiness, the number of charcoal particles in the sample, and their distribution.

Electrical resistivity as an indicator that characterizes the structural features of carbon materials shows an improvement in the structural ordering of biocokes when using sunflower husk additives up to 3 wt.% compared to the reference one. The use of other additives leads to a decrease in the quality of biocokes in this indicator (Fig. 3). With an increase in the number of additives, electrical resistivity increases, although not linearly.

Therefore, the addition of sunflower husk up to 3 wt.% leads to an improvement in the physical and mechanical properties of biocokes, which can be explained by the presence of a certain amount of oily substances [110, 111], which during thermal destruction, positively affect the process of formation and properties of biocoke. Straw pellet additives up to 3 wt.% positively affect structural strength and abrasive

Table 6 Yield, proximate analysis indicators, particles size distribution, and physical and mechanical properties of biocokes obtained from coal mixtures with biomass additives

Sample		Yield, %	Proximate analysis, %			Particles size distribution, %					Structural strength, %	Abrasive hardness, mg	Electrical resistivity, mΩ·m
Blend			A^d	V^d	S_t^d	>40 mm	40–25 mm	25–10 mm	10–5 mm	<5 mm			
Reference coke		73.9	11.9	1.0	1.36	88.4	5.1	0.9	1.2	4.4	72.3	105.0	13.57
Biocokes (wood chips addition, wt. %)	1	72.8	11.9	1.3	1.35	86.9	4.0	1.6	1.1	6.4	69.3	106.1	14.26
	3	71.4	11.8	1.5	1.32	83.2	5.5	2.1	1.4	7.8	64.7	119.3	14.99
	5	69.4	11.6	2.0	1.29	82.1	5.8	2.0	1.6	8.5	61.6	84.7	15.36
	10	66.7	11.3	1.9	1.22	80.4	6.2	2.3	1.8	9.3	55.3	76.5	15.82
Biocokes (wood pellets addition, wt. %)	1	73.0	11.9	2.0	1.34	90.1	1.3	1.8	1.6	5.2	70.2	96.7	13.98
	3	71.7	11.8	1.2	1.31	87.1	4.3	3.5	1.7	3.4	71.1	88.2	14.17
	5	69.8	11.6	2.1	1.28	90.2	2.5	2.5	1.1	3.7	66.2	80.0	14.58
	10	67.3	11.4	1.5	1.2	85.9	2.7	2.3	1.5	7.6	62.0	70.0	15.18
	15	64.8	11.1	2.5	1.13	72.9	6.4	4.9	2.9	12.9	58.6	55.1	16.88
	30	59.0	10.0	2.5	1.05	31.4	23.9	9.5	12.8	22.4	49.2	44.0	17.57
	45	52.6	6.6	1.5	0.95	9.5	21.3	12.7	24.7	31.8	36.1	32.6	19.64
Biocokes (sunflower husk addition, wt. %)	1	73.1	11.8	1.4	1.34	92.9	1.4	0.7	1.0	4.0	75.4	119.5	13.48
	3	72.0	11.6	0.8	1.32	93.2	0.9	0.7	1.4	3.8	76.1	126.8	13.34
	5	70.2	11.4	2.0	1.29	80.0	6.5	4.2	1.4	7.9	68.7	106.0	13.62
Biocokes (straw addition, wt. %)	1	73.1	11.9	1.1	1.35	90.0	3.4	1.4	1.1	4.1	73.8	127.4	13.80
	3	71.9	11.7	2.0	1.33	91.0	1.6	1.5	1.6	4.3	73.4	123.0	14.67
	5	70.0	11.6	1.8	1.30	85.8	2.0	3.8	1.7	6.7	67.4	101.2	15.18

Fig. 1 Effect of addition of biomass on structural strength of biocokes

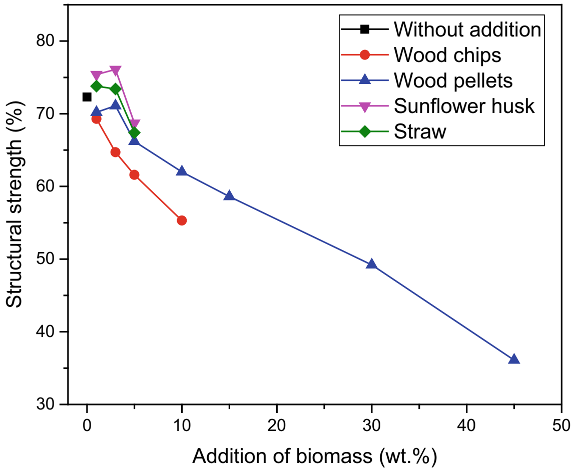
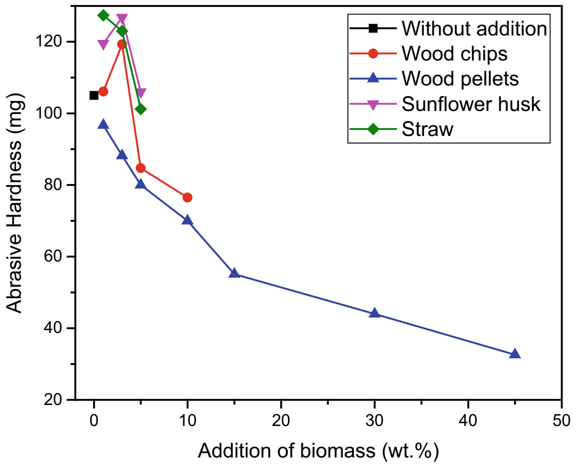


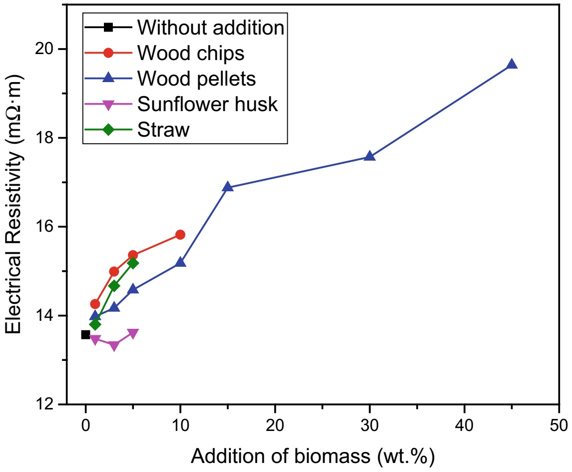
Fig. 2 Effect of addition of biomass on the abrasive hardness of biocokes



hardness, but electrical resistivity increases when using this type of additive. The use of wood additives shows a tendency to reduce the physical and mechanical properties of biocokes. At the same time, the use of pellets has a less negative effect on the structural features of biocokes (structural strength, electrical resistivity) than the addition of chips.

A study of the effect of adding a high proportion of wood pellets on the quality of biocokes demonstrates notable dependencies. Thus, the yield of biocokes decreases non-linearly and increases the yield from the expected one. The physical and mechanical properties of biocoke obtained with additives of 15 and 30 wt.% remain acceptable for non-BF productions. At the same time, inclusions of charcoal in the form of pellets are clearly observed, which, with an increase in the amount, are better separated from the bulk of the solid residue of coal pyrolysis.

Fig. 3 Effect of addition of biomass on electrical resistivity of biocokes



Therefore, the results of earlier studies are confirmed [80, 83], which shows the local effect of wood pellet additives on the change in the properties of the resulting biocoke.

Analysis of the obtained results shows that biomass additives affect the process and quality of biocoke production. The effect of influence is determined by qualitative and quantitative factors, namely the type, form, and proportion of the additive in a mixture with coal. The mechanism of the influence of biomass additives can be explained by the scheme of the co-pyrolysis of coals and biomass, which is presented in Fig. 4.

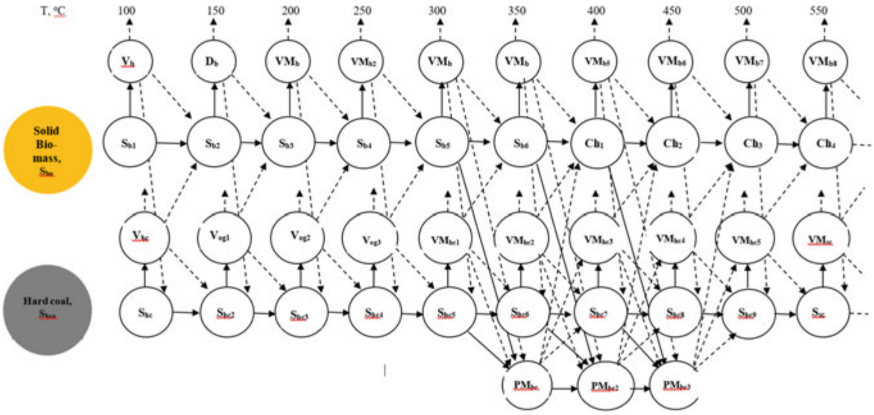


Fig. 4 Scheme of the mechanism of co-pyrolysis of coal and biomass: V_b—vapor of water from biomass; S_b—solid biomass; VM_b—volatile matter from raw and pyrolyzed biomass; V_{hc}—water vapor from hard coal; V_{og}—occluded gas from hard coal; S_{hc}—solid hard coal; VM_{hc}—volatile matter from hard coal; PM_{hc}—plastic layer from hard coal

The scheme shows the course of the process of co-pyrolysis of biomass and coal, namely drying and subsequent parallel and sequential processes of dehydration and condensation with the formation of liquid and solid products and depolymerization processes with the formation of volatile and tarry liquid substances, in the case of biomass pyrolysis; as well as dehydration processes followed by sequential-parallel polycondensation reactions with the formation of metastable phases in the case of coal pyrolysis.

Consequently, there is a transition from the solid state to the solid, a systematic but limited at each stage, decrease in the mass of the solid, a change in the yield of volatile matters, and the appearance, growth, and disappearance of the plastic layer of coal. The pyrolysis process is non-isothermal and continuous, forming and destroying new compounds. As can be seen from the scheme, during the co-pyrolysis of biomass and coal, different phases interact.

Biomass, namely cellulose and hemicellulose, begins to decompose before coal; thus, the volatile decomposition products formed in the charge further process the coal. Considering the predominantly oxygen-containing composition of volatile biomass, their effect on coal is oxidative, which ultimately reduces the caking ability of coals [82, 112–115].

The treatment of biomass with volatile pyrolysis products should affect the kinetics of the yield of steam-gas products of coal. In turn, with increasing temperature, higher molecular weight volatile products of coal act on solid biomass degradation products, processing charcoal.

In the coal pyrolysis process, all phases interact with each other, and each is involved in polycondensation. As a result, new metastable products are synthesized, namely liquid, solid and gaseous, forming phases of the next stage. Evidence of this should be the formation of various amounts of vapor–gas, liquid, and solid products. The most active changes occur within the temperature range of 250–500 °C when biomass decomposes and the coal plastic layer is formed.

It is also important to consider that under higher temperatures and industrial conditions, thermal degradation of biomass pyrolysis tar and light products of primary coal tar will take place. The yield level of various products is determined by the depth of transformations that coal and biomass undergo at the stages of pyrolysis. Therefore, it is necessary to distinguish between conclusions on the co-pyrolysis of biomass and coal, obtained based on pyrolysis under laboratory conditions, and industrial-scale ones.

Additionally, essential to note that during pyrolysis, the destruction-synthesis processes are limited by the rate of thermochemical transformations of the coal substance and not by heat transfer inside the coal particle.

Thus, the addition of biomass actively affects the process of thermal destruction of the charge and, subsequently, the qualitative indicators of the solid residue: proximate analysis, physical–mechanical and physical–chemical properties. Accordingly, using biomass additives makes it possible to obtain biocoke of different qualities for various production processes.

4 Conclusions

Studies on the production of biocoke under laboratory conditions and its study showed that the addition of biomass in the form of wood pellets, wood chips, pellets from sunflower husks, and pellets from straw into coal blend leads to a change in the properties of coke: yield, particles size distribution, structural strength, abrasive hardness, and electrical resistivity.

The use of up to 3 wt.% biomass pellet additives and 5 wt.% wood pellets do not lead to a deterioration in the granulometric composition of biocokes. At the same time, the output of large sizes (>25 mm) and small sizes (< 10 mm) changes noticeably when using the addition of wood chips and with more than 5 wt.% pellet additions.

Regarding structural strength, abrasive hardness, and electrical resistivity, biocokes obtained with the addition of sunflower husks have better characteristics. This can be explained by the presence of a residual amount of oily substances, which improve the caking of coal particles. The addition of sunflower husks generally carries fewer oxygen-containing groups, negatively affecting the co-pyrolysis process with coal.

Straw pellet additions up to 3 wt.% also do not adversely affect the particle's size distribution and structural strength, with a noticeable improvement in abrasive hardness. However, the electrical resistivity of biocokes obtained with the participation of straw increases.

The addition of wood leads to a decrease in the physical and mechanical properties of biocokes. However, the deterioration of properties is not linear, which is more clearly seen when studying the effect of increased wood pellet addition. At the same time, using chips compared to pellets has an even more negative impact. Therefore, the effect of the pellets is local in nature on the change in the properties of the resulting biocoke, and the effect of the chips can be considered volumetric due to the uniform distribution of the chips in the charge volume.

Using biocoke as a metallurgical fuel and reducing agent can improve the technical and economic performance of non-blast furnace industries by using carbon material with more suitable physical, mechanical, and physicochemical properties than conventional coke. In addition, using biomass additives is an environmentally friendly approach to obtaining carbon fuels. The advantages of using biomass as a component of coal blends in the coking process are the utilization of biomass; use of renewable raw materials, instead of fossil fuels, in particular, deficient coking coal; obtaining a new product, namely biocoke, the properties of which meet the modern requirements of consumers; reducing the negative impact on the environmental situation in the region and the world. The cost of biocoke may be lower than that of obtaining the corresponding grades of conventional coke. Therefore, using biomass additives to produce coke will solve complex problems in industrial regions and enterprises of ferrous metallurgy, agriculture, the chemical industry, and many others that process biomass.

Acknowledgements The presented results have been obtained within the framework of the scientific-research projects GP-512 "Co-gasification of carbon-containing raw materials during ultrathin coal seams gasification with a focus on hydrogen production" and GP-516 "Scientific and practical bases of low-rank coal gasification technology", state registrations No. 0123U100985 and No. 0123U101757 of the Ministry of Education and Science of Ukraine.

References

1. Gielen, D., Saygin, D., Taibi, E., Birat, J.: Renewables-based decarbonization and relocation of iron and steel making: a case study. J. Ind. Ecol. **24**, 1113–1125 (2020). https://doi.org/10.1111/jiec.12997
2. Vogl, V., Olsson, O., Nykvist, B.: Phasing out the blast furnace to meet global climate targets. Joule **5**, 2646–2662 (2021). https://doi.org/10.1016/j.joule.2021.09.007
3. Development of a Low CO2 Iron and Steelmaking Integrated Process Route for a Sustainable European Steel Industry (2018)
4. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal
5. United Nations Climate Change conference. https://en.wikipedia.org/wiki/United_Nations_Climate_Change_conference. Accessed 14 Apr 2023
6. Ritchie, H., Roser, M., Rosado, P.: CO2 and greenhouse gas emissions country profiles. https://ourworldindata.org/co2-and-greenhouse-gas-emissions. Accessed 14 Apr 2023
7. UNCTAD sets out actions to support least developed countries in the global low-carbon transition. https://unctad.org/news/unctad-sets-out-actions-support-least-developed-countries-global-low-carbon-transition. Accessed 14 Apr 2023
8. Tong, D., Zhang, Q., Zheng, Y., et al.: Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. Nature **572**, 373–377 (2019). https://doi.org/10.1038/s41586-019-1364-3
9. Vogl, V., Åhman, M., Nilsson, L.J.: Assessment of hydrogen direct reduction for fossil-free steelmaking. J. Clean. Prod. **203**, 736–745 (2018). https://doi.org/10.1016/j.jclepro.2018.08.279
10. Bataille, C.G.F.: Physical and policy pathways to net-zero emissions industry. WIREs Clim Change 11 (2020). https://doi.org/10.1002/wcc.633
11. Diez, M.A., Centeno, T.A., Amado-Fierro, Á.: Coal use for iron and steel production in low-carbon transition scenarios. In: The Coal Handbook, pp 493–546. Elsevier (2023)
12. Swennenhuis, F., de Gooyert, V., de Coninck, H.: Towards a CO2-neutral steel industry: justice aspects of CO2 capture and storage, biomass- and green hydrogen-based emission reductions. Energy Res. Soc. Sci. **88**, 102598 (2022). https://doi.org/10.1016/j.erss.2022.102598
13. Blast Furnace 2030- a vision for sustainable iron production. https://www.mpiuk.com/downloads/industry-papers/SI-Series-Paper-04-Blast-Furnace-2030-A-Vision-for-Sustainable-Iron-Production.pdf. Accessed 14 Apr 2023
14. Kim, J., Sovacool, B.K., Bazilian, M., et al.: Decarbonizing the iron and steel industry: a systematic review of sociotechnical systems, technological innovations, and policy options. Energy Res. Soc. Sci. **89**, 102565 (2022). https://doi.org/10.1016/j.erss.2022.102565
15. Koveria, A., Kieush, L., Svietkina, O., Perkov, Y.: Metallurgical coke production with biomass additives. Part 1. A review of existing practices. Can. Metall. Q. **59**, 417–429 (2020). https://doi.org/10.1080/00084433.2021.1916293
16. Suopajärvi, H., Kemppainen, A., Haapakangas, J., Fabritius, T.: Extensive review of the opportunities to use biomass-based fuels in iron and steelmaking processes. J. Clean. Prod. **148**, 709–734 (2017). https://doi.org/10.1016/j.jclepro.2017.02.029

17. Lyalyuk, V.P., Tarakanov, A.K., Kassim, D.A.: Influence of the reactivity of coke on blast-furnace performance. Coke Chem **54**, 47–52 (2011). https://doi.org/10.3103/S1068364X11020050
18. Wang, C., Wei, W., Mellin, P., et al.: Utilization of Biomass for Blast Furnace in Sweden-Report I: Biomass Availability and Upgrading Technologies. KTH (2013)
19. Oliveira, T.L., Assis, P.S., Leal, E.M., Ilídio, J.R.: Study of biomass applied to a cogeneration system: a steelmaking industry case. Appl. Therm. Eng. **80**, 269–278 (2015). https://doi.org/10.1016/j.applthermaleng.2015.01.002
20. Wiklund, C.-M., Helle, M., Kohl, T., et al.: Feasibility study of woody-biomass use in a steel plant through process integration. J. Clean. Prod. **142**, 4127–4141 (2017). https://doi.org/10.1016/j.jclepro.2016.09.210
21. Anand, A., Gautam, S., Ram, L.C.: Feedstock and pyrolysis conditions affect suitability of biochar for various sustainable energy and environmental applications. J. Anal. Appl. Pyrol. **170**, 105881 (2023). https://doi.org/10.1016/j.jaap.2023.105881
22. Fu, J.-X., Zhang, C., Hwang, W.-S., et al.: Exploration of biomass char for CO2 reduction in RHF process for steel production. Int. J. Greenhouse Gas Control **8**, 143–149 (2012). https://doi.org/10.1016/j.ijggc.2012.02.012
23. Ahmed, H.M., Mousa, E.A., Larsson, M., Viswanathan, N.N.: Recent Trends in Ironmaking Blast Furnace Technology to Mitigate CO2 Emissions: Top Charging Materials. In: Cavaliere, P. (ed.) Ironmaking and Steelmaking Processes, pp. 101–124. Springer International Publishing, Cham (2016)
24. Straka, T.J.: Charcoal as a fuel in the ironmaking and smelting industries. AHS **06**, 56–64 (2017). https://doi.org/10.4236/ahs.2017.61004
25. da Rocha, E.P., Guilherme, V.S., de Castro, J.A., et al.: Analysis of synthetic natural gas injection into charcoal blast furnace. J. Market. Res. **2**, 255–262 (2013). https://doi.org/10.1016/j.jmrt.2013.02.015
26. Babich, A., Senk, D., Fernandez, M.: Charcoal behaviour by its injection into the modern blast furnace. ISIJ Int. **50**, 81–88 (2010). https://doi.org/10.2355/isijinternational.50.81
27. Scarpinella, C.A., Cyro, T., Tagusagawa, S.Y., et al.: Charcoal Ironmaking: A Contribution for CO2 Mitigation. Cancun, Mexico (2011)
28. Feliciano-Bruzual, C.: Charcoal injection in blast furnaces (Bio-PCI): CO2 reduction potential and economic prospects. J. Market. Res. **3**, 233–243 (2014). https://doi.org/10.1016/j.jmrt.2014.06.001
29. Ueda, S., Watanabe, K., Yanagiya, R., Inoue, T.: Optimization of biomass utilization for reducing CO2 in ironmaking process. J. Iron. Steel Res. Int. **16**, 593–599 (2009)
30. Wang, C., Larsson, M., Lövgren, J., et al.: Injection of solid biomass products into the blast furnace and its potential effects on an integrated steel plant. Energy Procedia **61**, 2184–2187 (2014). https://doi.org/10.1016/j.egypro.2014.12.105
31. Mousa, E., Sjöblom, K.: Modeling and optimization of biochar injection into blast furnace to mitigate the fossil CO2 emission. Sustainability **14**, 2393 (2022). https://doi.org/10.3390/su14042393
32. Ahmed, H.M., Viswanathan, N., Bjorkman, B.: Composite pellets - a potential raw material for iron-making. Steel Res. Int. **85**, 293–306 (2014). https://doi.org/10.1002/srin.201300072
33. MacPhee, J.A., Gransden, J.F., Giroux, L., Price, J.T.: Possible CO2 mitigation via addition of charcoal to coking coal blends. Fuel Process. Technol. **90**, 16–20 (2009). https://doi.org/10.1016/j.fuproc.2008.07.007
34. Brazil at steel decarbonization crossroads; charcoal, gas short-term options
35. Khawaja, A.S., Zaheer, M.A., Ahmad, A., et al.: Advances in limitations and opportunities of clean biofuel production to promote decarbonization. Fuel **342**, 127662 (2023). https://doi.org/10.1016/j.fuel.2023.127662
36. Malode, S.J., Prabhu, K.K., Mascarenhas, R.J., et al.: Recent advances and viability in biofuel production. Energy Conv. Manage.: X **10**, 100070 (2021). https://doi.org/10.1016/j.ecmx.2020.100070

37. Kiehbadroudinezhad, M., Merabet, A., Ghenai, C., et al.: The role of biofuels for sustainable MicrogridsF: a path towards carbon neutrality and the green economy. Heliyon **9**, e13407 (2023). https://doi.org/10.1016/j.heliyon.2023.e13407
38. Sharma, S., Kundu, A., Basu, S., et al.: Sustainable environmental management and related biofuel technologies. J. Environ. Manage. **273**, 111096 (2020). https://doi.org/10.1016/j.jenvman.2020.111096
39. Jha, S., Nanda, S., Acharya, B., Dalai, A.K.: A review of thermochemical conversion of waste biomass to biofuels. Energies **15**, 6352 (2022). https://doi.org/10.3390/en15176352
40. Freiberg, A., Scharfe, J., Murta, V.C., Seidler, A.: The use of biomass for electricity generation: a scoping review of health effects on humans in residential and occupational settings. IJERPH **15**, 354 (2018). https://doi.org/10.3390/ijerph15020354
41. Janiszewska, D., Ossowska, L.: The role of agricultural biomass as a renewable energy source in European union countries. Energies **15**, 6756 (2022). https://doi.org/10.3390/en15186756
42. Scarlat, N., Dallemand, J.-F., Fahl, F.: Biogas: developments and perspectives in Europe. Renew. Energy **129**, 457–472 (2018). https://doi.org/10.1016/j.renene.2018.03.006
43. Sangeetha, J., Shettar, A.K., Thangadurai, D.: Nanomaterials from biomass: an update. In: Kharissova, O.V., Martínez, L.M.T., Kharisov, B.I. (eds.) Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications, pp. 1–18. Springer International Publishing, Cham (2021)
44. Zhang, Y., Xu, W., Wang, X., et al.: From biomass to nanomaterials: a green procedure for preparation of holistic bamboo multifunctional nanocomposites based on formic acid rapid fractionation. ACS Sustain. Chem. Eng. **7**, 6592–6600 (2019). https://doi.org/10.1021/acssuschemeng.8b05502
45. Raja, S., Mattoso, L.H.C., Moreira, F.K.V.: Biomass-derived nanomaterials. In: Balakumar, S. (ed.) Rajendran S, Naushad Mu, pp. 243–270. Nanostructured Materials for Energy Related Applications. Springer International Publishing, Cham (2019)
46. Kieush, L., Koveria, A.: Analysis and evaluation of the nanomaterials' impact on the environment. Nanosistemi, Nanomateriali, Nanotehnologii **18**, 141–156 (2020)
47. Kieush, L., Koveria, A., Hrubyak, A., et al.: Corn stalks as ecofriendly sources for carbon nanomaterials. In: 2018 IEEE 8th International Conference Nanomaterials: Application & Properties (NAP), pp 1–4. IEEE, Zatoka, Ukraine (2018)
48. Lackner, M.: Biopolymers. In: Chen, W.-Y., Suzuki, T., Lackner, M. (eds.) Handbook of Climate Change Mitigation and Adaptation, pp. 3211–3230. Springer International Publishing, Cham (2017)
49. Coppola, G., Gaudio, M.T., Lopresto, C.G., et al.: Bioplastic from renewable biomass: a facile solution for a greener environment. Earth Syst. Environ. **5**, 231–251 (2021). https://doi.org/10.1007/s41748-021-00208-7
50. Moshood, T.D., Nawanir, G., Mahmud, F., et al.: Sustainability of biodegradable plastics: new problem or solution to solve the global plastic pollution? Current Res. Green Sustain. Chem. **5**, 100273 (2022). https://doi.org/10.1016/j.crgsc.2022.100273
51. Reshmy, R., Thomas, D., Philip, E., et al.: Bioplastic production from renewable lignocellulosic feedstocks: a review. Rev. Environ. Sci. Biotechnol. **20**, 167–187 (2021). https://doi.org/10.1007/s11157-021-09565-1
52. Mokrzycki, J., Michalak, I., Rutkowski, P.: Biochars obtained from freshwater biomass—green macroalga and hornwort as Cr(III) ions sorbents. Biomass Conv. Bioref. **11**, 301–313 (2021). https://doi.org/10.1007/s13399-020-00649-6
53. Marzeddu, S., Décima, M.A., Camilli, L., et al.: Physical-chemical characterization of different carbon-based sorbents for environmental applications. Materials **15**, 7162 (2022). https://doi.org/10.3390/ma15207162
54. Frolova, L., Kharytonov, M., Klimkina, I., et al.: Adsorption purification of waste water from chromium by ferrite manganese. E3S Web Conf. **168**, 00026 (2020). https://doi.org/10.1051/e3sconf/202016800026
55. Frolova, L., Kharytonov, M., Klimkina, I., et al.: Investigation of the adsorption of ions chromium by mean biochar from coniferous trees. Appl. Nanosci. **12**, 1123–1129 (2022). https://doi.org/10.1007/s13204-021-01995-1

56. Danso, F., Agyare, W.A., Bart-Plange, A.: Benefits and costs of cultivating rice using biochar-inorganic fertilizer combinations. J. Agricult. Food Res. **11**, 100491 (2023). https://doi.org/10.1016/j.jafr.2022.100491
57. Bruun, S., Clauson-Kaas, S., Bobuľská, L., Thomsen, I.K.: Carbon dioxide emissions from biochar in soil: role of clay, microorganisms and carbonates: CO $_2$ emissions from biochar in soil. Eur. J. Soil Sci. **65**, 52–59 (2014). https://doi.org/10.1111/ejss.12073
58. Bai, X., Zhang, S., Shao, J., et al.: Exploring the negative effects of biochars on the germination, growth, and antioxidant system of rice and corn. J. Environ. Chem. Eng. **10**, 107398 (2022). https://doi.org/10.1016/j.jece.2022.107398
59. Adilson de Castro, J., de Medeiros, G.A., de Oliveira, E.M., et al.: The mini blast furnace process: an efficient reactor for green pig iron production using charcoal and hydrogen-rich gas: a study of cases. Metals **10**, 1501 (2020). https://doi.org/10.3390/met10111501
60. Wiklund, C.-M., Pettersson, F., Saxén, H.: Optimization of a steel plant with multiple blast furnaces under biomass injection. Metall. Materi. Trans. B **44**, 447–458 (2013). https://doi.org/10.1007/s11663-012-9790-8
61. Mousa, E., Wang, C., Riesbeck, J., Larsson, M.: Biomass applications in iron and steel industry: an overview of challenges and opportunities. Renew. Sustain. Energy Rev. **65**, 1247–1266 (2016). https://doi.org/10.1016/j.rser.2016.07.061
62. Fick, G., Mirgaux, O., Neau, P., Patisson, F.: Using biomass for pig iron production: a technical, environmental and economical assessment. Waste Biomass Valor **5**, 43–55 (2014). https://doi.org/10.1007/s12649-013-9223-1
63. Suopajärvi, H., Pongrácz, E., Fabritius, T.: Bioreducer use in Finnish blast furnace ironmaking – analysis of CO2 emission reduction potential and mitigation cost. Appl. Energy **124**, 82–93 (2014). https://doi.org/10.1016/j.apenergy.2014.03.008
64. Kieush, L., Koveria, A., Boyko, M., et al.: Influence of biocoke on iron ore sintering performance and strength properties of sinter. Min. Miner. Depos. **16**, 55–63. https://doi.org/10.33271/mining16.02.055
65. Kieush, L., Koveria, A., Boyko, M., et al.: Walnut shells as a potential fuel for iron ore sintering. MSF **1045**, 127–140 (2021). https://doi.org/10.4028/www.scientific.net/MSF.1045.127
66. Kieush, L., Boyko, M., Koveria, A., et al.: Manganese sinter production with wood biomass application. KEM **844**, 124–134 (2020). https://doi.org/10.4028/www.scientific.net/KEM.844.124
67. Kieush, L., Koveria, A., Zhu, Z.Q., et al.: Application of biomass pellets for iron ore sintering. MSF **1045**, 17–31 (2021). https://doi.org/10.4028/www.scientific.net/MSF.1045.17
68. Kieush, L., Boyko, M., Koveria, A., et al.: Utilization of the prepyrolyzed technical hydrolysis lignin as a fuel for iron ore sintering. EEJET **1**, 34–39 (2019). https://doi.org/10.15587/1729-4061.2019.154082
69. Kieush, L., Yaholnyk, M., Boyko, M., et al.: Study of biomass utilisation in the iron ore sintering. Acta Metall. Slovaca **25**, 55 (2019). https://doi.org/10.12776/ams.v1i1.1225
70. Zandi, M., Martinez-Pacheco, M., Fray, T.A.T.: Biomass for iron ore sintering. Miner. Eng. **23**, 1139–1145 (2010). https://doi.org/10.1016/j.mineng.2010.07.010
71. Praes, G.E., de Arruda, J.D., Lemos, L.R., Tavares, R.P.: Assessment of iron ore pellets production using two charcoals with different content of materials volatile replacing partially anthracite fines. J. Market. Res. **8**, 1150–1160 (2019). https://doi.org/10.1016/j.jmrt.2018.09.003
72. Kieush, L., Schenk, J., Koveria, A., et al.: 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**, 722 (2023). https://doi.org/10.3390/met13040722
73. Bianco, L., Baracchini, G., Cirilli, F., et al.: Sustainable electric arc furnace steel production: GREENEAF. Berg Huettenmaenn Monatsh **158**, 17–23 (2013). https://doi.org/10.1007/s00501-012-0101-0

74. Suer, J., Ahrenhold, F., Traverso, M.: Carbon footprint and energy transformation analysis of steel produced via a direct reduction plant with an integrated electric melting unit. J. Sustain. Metall. **8**, 1532–1545 (2022). https://doi.org/10.1007/s40831-022-00585-x
75. Sommerfeld, M., Friedrich, B.: Replacing fossil carbon in the production of ferroalloys with a focus on bio-based carbon: a review. Minerals **11**, 1286 (2021). https://doi.org/10.3390/min11111286
76. Surup, G.R., Trubetskaya, A., Tangstad, M.: Charcoal as an alternative reductant in ferroalloy production: a review. Processes **8**, 1432 (2020). https://doi.org/10.3390/pr8111432
77. Yuan, P., Shen, B., Duan, D., et al.: Study on the formation of direct reduced iron by using biomass as reductants of carbon containing pellets in RHF process. Energy **141**, 472–482 (2017). https://doi.org/10.1016/j.energy.2017.09.058
78. Han, H., Duan, D., Yuan, P., Li, D.: Biomass reducing agent utilisation in rotary hearth furnace process for DRI production. Ironmak. Steelmak. **42**, 579–584 (2015). https://doi.org/10.1179/1743281215Y.0000000001
79. Buergler, T., Di Donato, A.: Biomass gasification for DRI production. Rev. Met. Paris **106**, 429–433 (2009). https://doi.org/10.1051/metal/2009075
80. Kieush, L., Schenk, J., Pfeiffer, A., et al.: Investigation on the influence of wood pellets on the reactivity of coke with CO2 and its microstructure properties. Fuel **309**, 122151 (2022). https://doi.org/10.1016/j.fuel.2021.122151
81. Rejdak, M., Wojtaszek-Kalaitzidi, M., Gałko, G., et al.: A study on bio-coke production—the influence of bio-components addition on coke-making blend properties. Energies **15**, 6847 (2022). https://doi.org/10.3390/en15186847
82. Yustanti, E., Wardhono, E.Y., Mursito, A.T., Alhamidi, A.: Types and composition of biomass in biocoke synthesis with the coal blending method. Energies **14**, 6570 (2021). https://doi.org/10.3390/en14206570
83. Bazaluk, O., Kieush, L., Koveria, A., et al.: Metallurgical coke production with biomass additives: study of biocoke properties for blast furnace and submerged arc furnace purposes. Materials **15**, 1147 (2022). https://doi.org/10.3390/ma15031147
84. Vassilev, S.V., Baxter, D., Andersen, L.K., Vassileva, C.G.: An overview of the chemical composition of biomass. Fuel **89**, 913–933 (2010). https://doi.org/10.1016/j.fuel.2009.10.022
85. Castro Díaz, M., Zhao, H., Kokonya, S., et al.: The effect of biomass on fluidity development in coking blends using high-temperature SAOS rheometry. Energy Fuels **26**, 1767–1775 (2012). https://doi.org/10.1021/ef2018463
86. El-Tawil, A.A., Björkman, B., Lundgren, M., et al.: Influence of bio-coal properties on carbonization and bio-coke reactivity. Metals **11**, 1752 (2021). https://doi.org/10.3390/met11111752
87. Moghtaderi, B., Meesri, C., Wall, T.F.: Pyrolytic characteristics of blended coal and woody biomass. Fuel **83**, 745–750 (2004). https://doi.org/10.1016/j.fuel.2003.05.003
88. Di Nola, G., de Jong, W., Spliethoff, H.: TG-FTIR characterization of coal and biomass single fuels and blends under slow heating rate conditions: partitioning of the fuel-bound nitrogen. Fuel Process. Technol. **91**, 103–115 (2010). https://doi.org/10.1016/j.fuproc.2009.09.001
89. Lu, K.-M., Lee, W.-J., Chen, W.-H., Lin, T.-C.: Thermogravimetric analysis and kinetics of co-pyrolysis of raw/torrefied wood and coal blends. Appl. Energy **105**, 57–65 (2013). https://doi.org/10.1016/j.apenergy.2012.12.050
90. Vuthaluru, H.B.: Thermal behaviour of coal/biomass blends during co-pyrolysis. Fuel Process. Technol. **85**, 141–155 (2004). https://doi.org/10.1016/S0378-3820(03)00112-7
91. Onenc, S., Retschitzegger, S., Evic, N., et al.: Characteristics and synergistic effects of co-combustion of carbonaceous wastes with coal. Waste Manage. **71**, 192–199 (2018). https://doi.org/10.1016/j.wasman.2017.10.041
92. Zhang, L., Xu, S., Zhao, W., Liu, S.: Co-pyrolysis of biomass and coal in a free fall reactor. Fuel **86**, 353–359 (2007). https://doi.org/10.1016/j.fuel.2006.07.004
93. Panwar, N., Gajera, B., Jain, S., Salvi, B.: Thermogravimetric studies on co-pyrolysis of raw/torrefied biomass and coal blends. Waste Manag Res **38**, 1259–1268 (2020). https://doi.org/10.1177/0734242X19896624

94. Sadhukhan, A.K., Gupta, P., Goyal, T., Saha, R.K.: Modelling of pyrolysis of coal–biomass blends using thermogravimetric analysis. Biores. Technol. **99**, 8022–8026 (2008). https://doi.org/10.1016/j.biortech.2008.03.047
95. Yang, H., Yan, R., Chen, H., et al.: Characteristics of hemicellulose, cellulose and lignin pyrolysis. Fuel **86**, 1781–1788 (2007). https://doi.org/10.1016/j.fuel.2006.12.013
96. ASTM D3172–13; Standard Practice for Proximate Analysis of Coal and Coke. ASTM International: West Conshohocken (2013)
97. Kieush, L., Koveria, A., Schenk, J., et al.: Investigation into the effect of multi-component coal blends on properties of metallurgical coke via petrographic analysis under industrial conditions. Sustainability **14**, 9947 (2022). https://doi.org/10.3390/su14169947
98. ISO/DTS 4699, Hard Coal — Determination of plastometric indices — Manual Sapozhnikov Penetration Plastometer method
99. ISO/TC 27/SC 5 N936 - ISO/NP 4699, Hard Coal - Determination of plastometric indices - Manual Sapozhnikov Penetration Plastometer method
100. ISO 7404–2:2009; Methods for the Petrographic Analysis of Coals—Part 2: Methods of Preparing Coal Samples (2009)
101. ISO 7404–3:2009; Methods for the Petrographic Analysis of Coals—Part 3: Method of Determining Maceral Group Composition (2009)
102. ISO 7404–5:2009; Methods for the Petrographic Analysis of Coals—Part 5: Method of Determining Microscopically the Reflectance of Vitrinite (2009)
103. Haidai, O.A., Pavlychenko, A.V., Koveria, A.S., et al.: Determination of granulometric composition of technogenic raw materials for producing composite fuel. Nauk visn nat hirn univ 52–58 (2022). https://doi.org/10.33271/nvngu/2022-4/052
104. Sumbane-Prinsloo, L., Bunt, J., Piketh, S., et al.: The influence of particle size on the thermal performance of coal and its derived char in a Union stove. Energy Geosci. **2**, 148–159 (2021). https://doi.org/10.1016/j.engeos.2020.08.001
105. Kühn, T., Bunt, J.R., Neomagus, H.W.J.P., et al.: Coal-derived low smoke fuel assessment through coal stove combustion testing. J. Anal. Appl. Pyrol. **126**, 158–168 (2017). https://doi.org/10.1016/j.jaap.2017.06.012
106. ASTM D293/D293M-18; Standard Test Method for the Sieve Analysis of Coke; ASTM International; West Conshohocken
107. GOST 9521–2017; Hard Coals. Method for the Determination of Coking Property (2017)
108. ISO 10143:2019; Carbonaceous Materials for the Production of Aluminium—Calcined Coke for Electrodes—Determination of the Electrical Resistivity of Granules (2019)
109. Rouget, G., Majidi, B., Picard, D., et al.: Electrical resistivity measurement of petroleum coke powder by means of four-probe method. Metall. Materi. Trans. B **48**, 2543–2550 (2017). https://doi.org/10.1007/s11663-017-1022-9
110. Gotor, A.A., Rhazi, L.: Effects of refining process on sunflower oil minor components: a review. OCL **23**, D207 (2016). https://doi.org/10.1051/ocl/2016007
111. Carelli, A.A., Frizzera, L.M., Forbito, P.R., Crapiste, G.H.: Wax composition of sunflower seed oils. J Amer Oil Chem Soc **79**, 763–768 (2002). https://doi.org/10.1007/s11746-002-0556-9
112. Montiano, M.G., Díaz-Faes, E., Barriocanal, C.: Effect of briquette composition and size on the quality of the resulting coke. Fuel Process. Technol. **148**, 155–162 (2016). https://doi.org/10.1016/j.fuproc.2016.02.039
113. Montiano, M.G., Díaz-Faes, E., Barriocanal, C., Alvarez, R.: Influence of biomass on metallurgical coke quality. Fuel **116**, 175–182 (2014). https://doi.org/10.1016/j.fuel.2013.07.070
114. Mochizuki, Y., Naganuma, R., Tsubouchi, N.: Influence of inherently present oxygen-functional groups on coal fluidity and coke strength. Energy Fuels **32**, 1657–1664 (2018). https://doi.org/10.1021/acs.energyfuels.7b03774
115. Tsubouchi, N., Mochizuki, Y., Naganuma, R., et al.: Influence of inherent oxygen species on the fluidity of coal during carbonization. Energy Fuels **30**, 2095–2101 (2016). https://doi.org/10.1021/acs.energyfuels.5b02914