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MODERN USE OF BIOCHAR IN VARIOUS TECHNOLOGIES AND INDUSTRIES. A REVIEW

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Abstract. The article analyzes the use of biochar in various industries and the national economy (as a sorbent, fuel, reducing agent in the metallurgical industry, a component of coal coke blends, biocomposites, modification of explosives, fertilizers, *etc.*) It is noted that the direction of use depends on the quality and characteristics of biochar (size, physical properties, chemical composition), which are determined by the nature of the raw material, its chemical composition and carbonization temperature.

Keywords: biochar; fuel; metallurgical technology; biocomposites; modification of explosives; biochar in agriculture; sorbent.

1. Use of Biochar in Metallurgical Technology

Charcoal (biochar) is a solid fuel obtained from wood (or biomass) by heating it to high temperatures without air or with very limited air access. It is made of hardwood raw materials and biomass unsuitable for construction and mechanical processing. The yield of charcoal from the mass of dry wood is 35–40 %. In industry, charcoal is produced in retorts or kilns, while in artisanal production, charcoal is burned in piles (bonfires). The calorific value depends on the final heating temperature and the production methods: for stove coal, 6500–7400 $kcal \cdot kg^{-1}$, for heap-burned coal, 8100 $kcal \cdot kg^{-1}$. Charcoal contains 65–70 % of non-volatile carbon, 30 % of volatile matter, and less than 5 % of ash[1–3]. Charcoal ash derived from biomass contains mainly oxides of silicon (SiO_2), aluminum (Al_2O_3), iron (Fe_2O_3), calcium (CaO), magnesium (MgO), sodium (Na_2O), potassium (K_2O), and phosphorus (P_2O_5)[4].

In the 19th century, charcoal was the main fuel in the steel industry. From about 1840, the American steel industry began to switch from charcoal to coal or coke but cast-iron production using charcoal increased until 1890 and remained high throughout the nineteenth century. The decline in the share of charcoal in cast iron production was due to changes in technology (larger blast furnaces with increased height and charcoal could not support larger overburden) and price (new production centers required huge amounts of fuel that local forests could not sustain, resulting in higher fuel transportation costs)[5].

Metallurgical production requires the use of carbon and hydrogen-containing reducing agents such as coke, coal and natural gas. The quality of coke is one of the main parameters that determine the progress and results of blast furnace smelting[6–8]. Given that coke is the most expensive component of the cast iron charge, the task of reducing its consumption is always relevant. It can be solved by replacing coke with less expensive energy sources[9].

In recent years, there has been renewed interest in the use of charcoal derived from biomass in blast furnace smelting, due to both environmental and economic aspects.

Among the various proposed strategies, the use of biomass has the potential to significantly reduce greenhouse gas emissions in the coke and blast furnace production system in the integrated steelmaking process[10]. In addition, the study notes that the integration of biomass into the cast iron production process can reduce carbon dioxide emissions by 31–57 %[11].

When carbon fuels are burned, greenhouse gas CO_2 is released into the atmosphere. In terms of greenhouse gas emissions, the crucial difference between fossil fuels and biomass is the period over which CO_2 is released. Since the natural process that converts CO_2 from the atmosphere into fossil fuels takes millions of years, CO_2 emitted from the combustion of this type of fuel is considered a "new" greenhouse gas. Thus, it contributes to

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an increase in the concentration of greenhouse gases in the atmosphere. On the other hand, burning biomass releases CO_2, which is balanced by CO_2 captured during its growth. Thus, the argument is that biomass is considered "greenhouse gas neutral"[10,12]. According to[10,13,14] replacing fossil fuels consumed in the cast iron production process with biomass can maintain both the carbon content needed for reduction and the energy needed for melting while reducing greenhouse gas emissions.

Untreated biomass, whether from trees, grasses, or algae, cannot directly replace traditional fossil fuels used in cast iron production due to its high moisture content, low carbon content, and low calorific value[11]. Modern thermochemical conversion processes can be used for solid, liquid, and gaseous biochar production from biomass. Pyrolysis is necessary to produce carbon-rich charcoal. Wood is the most commonly used form of biomass for fuel production. For example, baked wood is produced by pyrolysis up to 300 °C, semi-charcoal is produced at about 400 °C, and various types of charcoal are produced by heating the raw material from 500 to 800 °C. Feedstocks suitable for producing solid reducing agents for iron and steel production include straw, sawmill waste, vegetable wood, and forest residues such as thinnings, stumps, and roots[10,14].

The Ultra-Low Carbon Dioxide Steelmaking (ULCOS) program, led by ArcelorMittal and supported by EU steel producers Tata Steel, Saaestahl, Thyssen Krupp Steel, Dillinger, Voestalpine, SSAB, Ilva and Ruukki, is a series of coordinated projects launched in 2004 aimed at delivering a breakthrough process technology to produce steel from iron ore with a CO_2 footprint of at least 50 % less than a benchmark high-tech steel mill. The top loading of biochar together with charge materials directly into the blast furnace is difficult due to its low mechanical strength. It is practiced only in small blast furnaces in Brazil (internal volume up to 700 m^3) and cannot be implemented in medium and large-scale furnaces.[15,16]

The efficient use of charcoal in metallurgical technology can be realized through the following options: use as a fuel in the clinkering of iron ores or as a component for the production of carbon composite agglomerates (CCA)[17,18]; as a component of briquettes[19]; use of biochar as a component of coal charges for the production of biocoke; injection into the bottom of the blast furnace, which allows for replacing a significant part of pulverized coal[10,15].

The agglomeration of metal ores and concentrates involves pelletizing them by clinkering, which is done by burning fuel in the pre-pelletized material, the clinker charge. Coke fines, which account for 3–5 % of the total weight of the clinker charge, can be partially or completely replaced by biomass fuel (wood of various species in the form of pellets and briquettes, or agricultural waste, such as sunflower, straw, walnut, corn, rice and buckwheat husks, tree leaves, sunflower husks)[17,20–22]. The addition of pyrolyzed biofuels to the sinter charge improves the gas permeability of the agglomerated layer. The particles of biomaterials are distributed among the charge granules quite evenly and increase the porosity of the layer. Also, when using pyrolyzed biomass, a higher vertical clinkering rate is observed than when using coke fines alone. However, biofuels are characterized by a higher reactivity than coke fines, which can reduce the yield and negatively affect the quality of the sinter. According to Cheng *et al.*[23] the use of coarse-grained or molded biofuels reduces the contact area, complicates O_2 diffusion, and, as a result, improves clinkering quality.

Introducing less expensive and scarce solid biofuels into the blast furnace as a part of pelletized iron ore material can be auspicious, provided that the metallurgical characteristics of this material are maintained or improved. The advantage of this material is that in the process of its heat hardening, it is partially reduced from the inside by gasification of the solid fuel carbon rolled inside, and then during melting it is reduced simultaneously from the surface by the reducing gases of the blast furnace and from the center of the piece by gasification of the residual carbon, which accelerates the rate of reduction of the entire piece and, accordingly, the productivity of the blast furnace[17].

According to Mousa *et al.*[19], biomass lignin can be used as a binder and reducing agent in briquettes for blast furnace melting. Traditional briquettes consist of various residues containing iron oxide, and cement is used as a binder to provide the required mechanical strength. It has been found that partial replacement of up to 25 % of cement with lignin increases the carbon content and produces mechanically strong briquettes.

The authors of[13] investigated the possibility of producing coke with the addition of charcoal and kraft lignite as components of the charge. Thus, biocokes were prepared by adding charcoal produced from young pruned pine stems and kraft lignin obtained in the pulp production process to coal in the amount of 2.5 %, 5 %, 7.5 %, and 10 %. Bituminous coking coal was used as the main clinkering component of the charge, characterized by a volatile matter yield of 23.1 % on a dry weight basis, a maximum Gieseler fluidity of 545 ddpm and a total moisture content of 10.9 %. The coking and charcoal were crushed using a jaw crusher and ground using a ring grinder. After grinding, the samples were sieved to the desired particle size. The particle size of coking coal was as follows: 70 % by weight was sieved to a size of 0.5–1.0 mm, and 30 % to a size of less than 0.5 mm. The smallest particle size of charcoal was 45–90 microns, and the largest was 1.0–2.0 mm. At the same time, the heating rate was 3.5 °C·min^{-1}, and the final process temperature was 1200 °C.

Comparison of the characteristics of the charge components showed the following: the carbon content in charcoal is much higher than in coking coal. The ash content of charcoal and kraft lignin is low compared to coking coal. It should be noted that the chemical composition of coal and charcoal ash differs significantly. Coal ash has a high proportion of acidic components SiO_2 and Al_2O_3, while charcoal ash has a high proportion of alkaline components CaO and MgO. The chemical composition of biomass ash largely depends on the type of biomass, its origin and pollutants from processing. A higher proportion of alkalis (Na_2O, K_2O) is found in coal ash.

Suopajärvi *et al.*[13] carried out compression tests using the Gleeble 3800 thermomechanical simulator to evaluate the cold strength of biocokes[24–27]. The addition of charcoal does not reduce the strength of biocokes compared to reference cokes. The high strength of biocokes was obtained by adding charcoal in the amount of 5 % with particle size of 125–250 microns. The results of optical microscopy showed that the soft coke mass in some cases penetrated the charcoal cell and baked there, thus contributing to the development of cold strength. By increasing the bulk density of the coal mixture from 634 to 750 kg·m^{-1}, the strength of biocokes increased significantly[13]. It should be noted that biocokes with the addition of charcoal showed a higher reactivity compared to control cokes.

Similar conclusions are presented in[14]. Thus, it is noted that the use of any type of material derived from biomass (forestry and agricultural waste, pulp and paper industry) in the coal mixture weakens the development of fluidity during the plastic phase, increases the reactivity of coke, and can also negatively affect its post-reaction strength. However, this is not necessarily negative for the blast furnace process, as the use of a more highly reactive carbon material reduces the temperature of the thermal reserve zone and enhances the reduction of iron oxide to metallic iron, which reduces the consumption of reducing agents[15].

It is believed that the reason for the increased reactivity of biocoke is the larger surface area and concentration of oxygen functional groups, which limit the development of fluidity by absorbing some of the volatile matters of coal and forming cross-links with oxygen. Thus, it is probably the most important to control the surface area and oxygen content of the biomass components that are mixed with coking coal[16].

Mathieson *et al.*[11] summarized the quality criteria for charcoal and showed that different properties are required for each application. For example, charcoal for fuel clinkering should have a low volatile content (< 3 %), high density, low reactivity, and particle size in the range of 0.3–3 mm. Charcoal for blast furnace injection should be characterized by a higher volatile yield (10–20 %), low ash, and alkali content.

Theoretically, it is possible to produce improved charcoal from biomass that is chemically and physically similar to coal and coke, but the cost of such fuel will not be competitive. In practice, it is relatively easy to achieve chemical similarity, but obtaining the required level of physical properties, such as density, mechanical strength, and reactivity, requires an excessive amount of processing and is not achievable at a reasonable cost[11].

Therefore, it is necessary to research and improve methods of processing biomass into charcoal, which will make it possible to predict and influence its physical properties, structure, and obtain fuel with a set of characteristics. Future research should also focus on understanding the impact of the biomass components lignin, cellulose, and hemicellulose on coal plasticity and coke quality.

The experience of using charcoal for injection at Arcelor Mittal's blast furnace in Monlevado, with a capacity of approximately 3000 tons of cast iron per day, is given in[28]. The charcoal and pulverized coal were grounded separately due to the significant difference in the Hardgrove index (HGI). The natural gas was injected together with the pulverized charcoal (CC) and pulverized coal (PC), with a total injection rate of up to 165 kg·t^{-1}.

Successful results of this technology of using charcoal to replace the part of the PC were obtained within the framework of a national project at SSAB in Ökselösund, Sweden. Thus, it was shown that the addition of charcoal (CC) is possible in the amount of 10 %. It has been established that due to the similarity of chemical and thermal properties of charcoal (CC) and pulverized coal (PC), the substitution ratio can be 1:1 in relation to the carbon in coke and pulverized coal, with no negative impact on the course of blast furnace melting[15].

According to the calculations of Mathieson *et al.*[11], the coke consumption in BF can be reduced by 23–30 kg·t^{-1} of cast iron by using charcoal as an injector for tuyeres, and by 4.5–9 kg·t^{-1} of cast iron by loading 5–10 % of charcoal by the amount of charge ore materials.

2. Use of Biochar for Fuel Production

The technology of using charcoal to produce fuel suspensions for diesel engines is also worthy to note. The advantage of suspensions using charcoal is a significantly lower ash content compared to coal, which causes a much lower level of abrasive wear. Long and Boyette[4] choose yellow poplar (Liriodendron tulipifera) as a raw material for carbonization. To obtain charcoal with a high calorific value, density, and low oxygen content, the raw material was pyrolyzed at 700 °C. The charcoal was then processed using a multi-stage grinding process, which resulted in micronized fuel particles. Thus, 90 % of the sample volume consisted of particles smaller than 50 microns. Analysis of physical and chemical properties of the charcoal particles showed that the absolute density of the particles ranges from 1525 kg·m^{-3} to 1667 kg·m^{-3}, and the higher heating value is in the range from 52.0144 MJ·m^{-3} to 60.5604 MJ·m^{-3}, which is much higher than the quality characteristics of diesel fuel, which has an average density of 851 kg·m^{-3} and a higher heating value (HHV) of 38.362.5 MJ·m^{-3}. The charcoal-based fuel suspension may be suitable for use in medium- and low-speed diesel engines.

Mahottamananda *et al.*[29] investigated the possibility of increasing the thermal stability and improving the ballistic properties of beeswax by introducing additives of ethylene vinyl acetate (EVA) and activated carbon (AC). Beeswax ($C_{46}H_{92}O$) is a naturally occurring substance that can be used as a solid propellant for hybrid rocket systems and as a replacement for paraffin fuel in hybrid rockets. Beeswax burns more efficiently than paraffin due to the oxygen molecule it contains. However, its low heat resistance and low mechanical properties limit its practical use. Studies have shown that the thermal stability of beeswax with ethylene vinyl acetate (EVA) and activated carbon (AC) additives has improved significantly. Experiments to evaluate such aspects of ballistic performance as a regression rate, characteristic velocity, and combustion efficiency were conducted using a laboratory hybrid rocket engine. The results showed that EVA and AC additives to beeswax increase the experimental combustion rate and efficiency. For example, the combustion efficiency of BW-based fuel was improved from 62 % to 94 % when 20 % ethylene vinyl acetate and 2 % activated carbon were added to the fuel.

3. Use of Biochar in Biocomposites

Recently, scientists have also focused on research in the field of composite materials using biomass, which is a renewable resource that ensures environmental and economic efficiency of its use. This helps to reduce the use of polymers derived from petroleum products that pollute the environment. A significant advantage of biocomposites containing recycled products of plant origin is their high ability to decompose into safe components compared to classical polymers that require the use of special processing technologies[30].

Delatorre *et al.*[31] evaluated fine particles of charcoal as potential reinforcing agents in biocomposites. The study examined fine fractions of charcoal obtained by pyrolysis of biomass at 400, 600 and 800 °C. The best result as a filler of the polymer matrix was obtained when using charcoal obtained at 800 °C due to its high porosity (81.08 %), fixed carbon content (96.77 %), hydrophobicity, and mechanical stability. It was found that changing the pyrolysis temperature of small fractions of charcoal significantly affected the flexural properties, elastic modulus, and strength of the manufactured biocomposites. Thus, these characteristics naturally increased with increasing pyrolysis temperature. The tensile strength of the prepared samples obtained at 400, 600, and 800 °C was 15.8 MPa, 16 MPa, and 23.5 MPa, respectively. These properties of charcoal will improve its interaction and increase compatibility with polymer matrices, they can reduce costs, and dependence on fossil sources (plastic and other petroleum products) and, therefore, reduce greenhouse gas emissions.

Taking into account the peculiarities of biocomposites use in various industries, it became necessary to study the impact of UV-C radiation on their quality characteristics, which can lead to negative consequences such as changes in color, mechanical properties, surface relief and weight loss. Therefore, understanding how charcoal affects the resistance of biocomposites to photodegradation is of paramount importance, especially when these materials are intended for outdoor use. Thus, Delatorre *et al.*[32] present the results of assessing the effect of UV-C radiation on the characteristics of charcoal depending on the pyrolysis temperature at which it was obtained. Eucalyptus saligna was used as a bio-raw material. Samples of this biomass were ground and predried in an oven at 103±2 °C. The composite samples contained a charcoal additive in the amount of 30 %. The pyrolysis was carried out in a muffle furnace at an initial temperature of 30 °C and a heating rate of 10 °C·min^{-1} until the final temperature was reached at 400, 600, and 800 °C. The resulting biocomposite samples were exposed to UV-C radiation for 15 days. The tests were carried out in a controlled environment with a constant temperature of 22 °C and relative humidity of 44 %. It was found that the charcoal obtained at 800 °C demonstrates excellent potential for bio-reinforcement in polymer matrices due to its high porosity (81.08 %) and hydrophobic properties. The results also showed an increase in tensile strength of 69.24 %, 68.98 %, and 54.38 % after UV-C radiation for the biocomposite samples with the addition of charcoal obtained at 400, 600, and 800 °C, respectively. Thus, it has been established that carbon filler is a relevant component of polymeric biocomposites due to its properties. Its use is beneficial for obtaining a more structurally stable material and positively affects the mechanical properties and biocomposite resistance to environmental factors. The protective effect of charcoal can be explained by its antioxidant effect, *i. e.*, due to its interaction with free active radicals formed during catalytic decomposition under the influence of environmental factors, the rate of oxidation and degradation of the material decreases.

Similar conclusions about the use of fine fractions of charcoal due to their resistance to UV-C radiation in biocomposites, which leads to an improvement in their mechanical properties, were made by Delatorre *et al.*[33]. Thus, the effect of adding coal fines to the polymer matrix of biocomposites in the amount of 10, 20, and 30 % was studied. A polymer composite without the addition of a fine coal fraction showed a significant decrease in strength after exposure to UV-C radiation compared to samples containing 10 and 20 % charcoal. Thus, an increase in a certain amount of coal fines minimizes the loss of material stability and its photodegradation under the influence of radiation. The samples with 20 % coal fines showed improved mechanical characteristics, which may be because filler particles prevent the polymer chains of the matrix from slipping. However, when more filler is added, for example, 30 %, the mechanical characteristics deteriorate. This phenomenon can be explained by the weak polymer-fiber interaction, voids and poor dispersion of fibers in the matrix, and the influence of factors such as filler size, shape, and type[34–37].

Biofuel (PKSBc) derived from palm oil waste can be used as a sustainable, environmentally friendly biofiller in rubber composites and becomes an alternative to carcinogenic carbon black (CB), which is widely used as a reinforcing filler in the rubber industry. The authors developed composite formulations that included carboxylated nitrile-butadiene rubber (XNBR) and carbon black/biofuel fillers in late ratios. The synergistic effect of using carbon black and biofuels as rubber fillers was investigated, and the rheological, physical, and mechanical properties of the final composite were studied. With the addition of 35 phr ($g\cdot 100\ g^{-1}$ of rubber) of biofuel, the hardness of the composite increased by about 18.8 %, with the addition of a mixture of carbon black/biofuel fillers in the ratio of 30/5 phr, the hardness of the composite increased by 31.6 % compared to the control sample. The high hardness of the composite of carboxylated nitrile-butadiene rubber (XNBR) with a mixed CB/PKSBc filler in the ratio of 30/5 phr is due to the high crosslinking density of the composite. The pores on the surface of the biofuel contribute to the creation of a 3D network that makes the composite rigid. Thus, the results of the work proved the effectiveness of using a mixture of carbon black and biofuels to improve the performance of the rubber composition and the possibility of reducing the environmental burden by utilizing palm oil waste and reducing the use of carcinogenic carbon black[37].

4. Use of Charcoal (Biochar) for the Modification of Explosives

Another area of charcoal use is its application for the modification of explosives, which was discussed in studies[38–42]. The effect of charcoal micropowders on the properties of ammonium nitrate fuel oil (ANFO) was studied in[43]. ANFO is a mixture of ammonium nitrate (NH_4NO_3) and fuel oil (FO). Typically, the oxygen component is industrial-grade ammonium nitrate (V) in tablets (AN-PP), which are manufactured for use as a solid oxidizer in explosive mixtures. Today, ANFO is one of the most popular explosives used in the mining industry worldwide, mainly due to its low manufacturing cost, ease of production, and wide possibilities for modifying explosive properties (not only by adjusting the content of fuel oil or nitrate but also by using other components). Microstructured charcoal in the form of a powder obtained by destructive distillation of wood was used for the study. The charcoal powders were characterized by a grain size of 90 μm (fine powder) and 1.5 mm (fine powder) and 1.18 mm (fine granules). Fuel oil, which is the combustible component, had a density of $800\ kg\cdot cm^{-3}$ and a kinetic viscosity of $13.6\ mm^2\cdot s^{-1}$. The mixing procedure lasted 20 minutes. To obtain the explosive, the microstructured charcoal was added to ANFO during the last 5 minutes of the mixing process. It was found that the use of charcoal micropowders leads to a decrease in the detonation rate compared to the values obtained from thermodynamic models. The experimental results also showed that the detonation rate depended on the grain size of the charcoal powder. Thus, the highest values of the detonation rate were obtained by adding 1.0 % of charcoal powder with a grain size of 90 μm, which can be explained by an increase in the chemical reaction zone and an increase in heat transfer. Consequently, the best results were obtained for the composition of the explosive mixture 94.5 : 4.5 : 1.0 (ammonium nitrate : fuel oil : charcoal).

5. Aspects and Advantages of Biochar Use in Agriculture

Good quality soil is needed to improve plant growth, using biochar can improve indicators such as organic matter (humus) content, trace element content, pH levels, and improve soil homogeneity. The use of biochar is an excellent solution for poor soils to improve their structure. This type of soil has a high density which is a negative factor for aeration[44], the porosity of biochar solves this problem[45]. Tests on the use of biochar with compost have shown a good effect. The decomposition period of compost is shorter than that of charcoal, which makes it possible to provide micronutrients to plants earlier. This application will allow a reasonable utilization of biomass and improve the efficiency of biochar under real agricultural conditions[46]. Biochar promotes redox reactions in the soil, which positively affects its quality. Resistance to rapid decomposition is also a positive factor, it is economically favourable because the material can remain on the fields for a long time and does not require additional application[47]. Studies have shown that the use of biochar increases the growth hormone in plants (ethylene), which favorably affects growth, maturity, and yield[48]. The use of biochar helps to solve such a problem as the reduction of organic matter in the soil, which occurs as a result of anthropogenic activities. Stability in the soil is ensured by the crystalline structure of the material[49]. The use of biochar makes it possible to return the plant waste product to agriculture and thus close the loop of the circular economy[50]. The systematic cycle of bio-coal from plant waste is shown in Figure. This process is significantly influenced by the technology of biochar production. The material obtained by low-temperature pyrolysis decomposes much longer, biochar from high-temperature pyrolysis has a shorter decomposition period. Biochar is widely used for the sorption of heavy metals in soil. Oxygenated functional groups on the surface of the material promote sorption[51]. The effect of using biochar depends on the soil type, for example, the interaction of clay particles is more deeply studied[52]. The interaction is significantly influenced by the particle size distribution of the material.

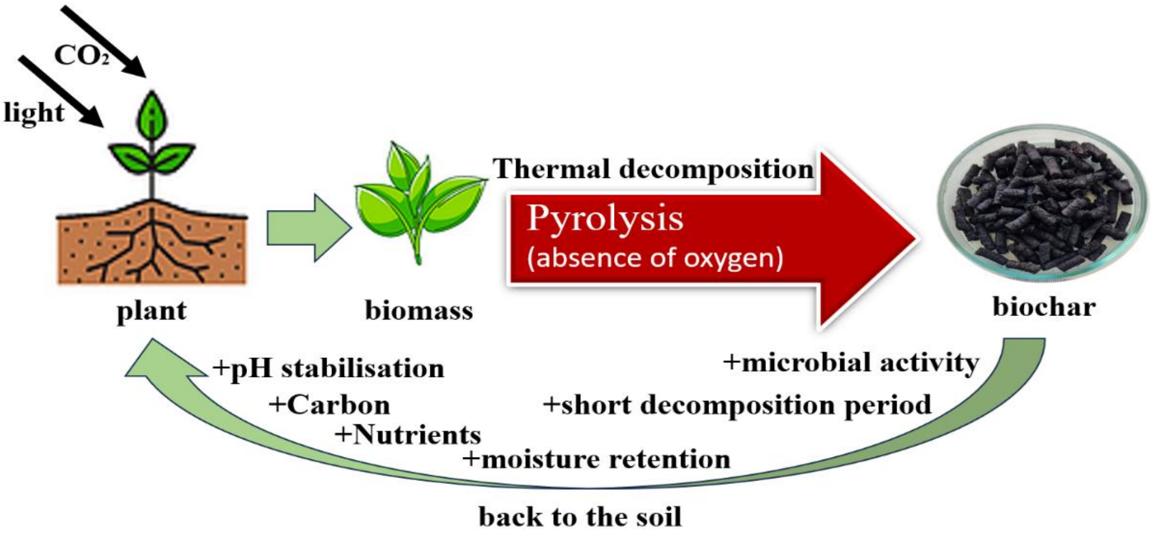

Fig. Systematic Cycle of Biochar in Soil and Plant system

The ability of biochar to nourish plants with micronutrients is another advantage of this product. For example, biochar from biomass contains a significant content of potassium, which has a positive effect on plant growth[53]. Biochar is also used for soil salinity control. Na+ ions help to reduce this indicator. The use of biochar helps to prevent the uptake of Na+ ions by plants, which has a positive effect on soil quality[54]. Studies have been conducted which showed that biochar from maize cobs and switch grass increases pH in acidic soils over a short period[55]. Studies have shown that material has a positive effect on legume crops by increasing the rate of nitrogen fixation. Also, the use of this product allows plants to grow and develop under conditions of salt stress[54]. The use of biochar helps to improve and increase nitrogen uptake[56]. The application of biochar from rice husk and inorganic NPK fertilizer on abandoned areas of gold mines with lettuce cultivation was investigated. The results showed that biochar prevents the uptake of heavy metals by plants and has a positive effect on the growth, development, and yield of lettuce[57]. The application of biochar affects the availability of different nutrients to plants. Phosphorus content in soil was investigated with and without biochar application. Biochar increases the phosphorus content by 45 %[58]. Biochar is often used together with compost, biomass or fertiliser. The effect of this combination is not always positive. Studies have shown that the activity of fertilizers is reduced in such applications[59]. Biochar produced at high pyrolysis temperatures decomposes faster than low-temperature pyrolyzed biochar. This factor affects the annual application of the material to the soil, there is no need to renew the process annually each growing season[60]. Most biochar species have hydroxyl and carboxyl groups that can bind to nitrogen and phosphorus. These complexes are often found in fertilizers[61]. Biochar allows nutrients to be retained in the soil and reduces nitrogen leaching. The application of biochar from wheat straw in amounts up to 1 % has been studied and this has reduced nitrogen leaching in various forms. This means that the biochar covalently binds to ammonia retaining it in the soil[62]. The use of biochar from maize cobs and fig trees in slow pyrolysis to 600 °C has a positive effect on maize growth. The low pH and increased functional surface increases the amount of free carboxyl carbon which favours the retention of cations on the surface of the biochar[63]. The reduction of organic matter in the soil favors an increase in the number of anaerobic microbes, which leads to the accumulation of ammonium nitrogen in the growing medium. In contact with air, ammonium nitrogen is converted to NO_3-N which leads to leaching, biochar reduces this process[64].

The pH level in the soil can be regulated by using biochar. The alkalinity or acidity of the material depends on the raw material from which it was obtained. Alkaline biochar is obtained from agricultural waste such as wheat straw, buckwheat straw, oat straw, *etc*.) Knowing the pH value of biochar it is possible to regulate pH of the soil by selecting the necessary proportion to be applied to the soil. This type of product contains a large amount of ash with many salts which increases the alkalinity[65]. Biochar with higher acidity is obtained from bovine and chicken manure[66]. Studies have shown that biochar has a positive effect on legume crops by increasing the rate of nitrogen fixation.

6. Use of Biochar as a Sorbent

6.1. Liquid Treatment

The characteristics of the different types of biochar is shown in Table, the data presented are obtained as an average of samples from different publications. The technological process for each type of feedstock is selected individually and varies from 200 °C to 850 °C, depending on the porosity and adsorption properties of the material. The intensive decomposition processes in biomass stop after 500 °C, while peat requires a higher temperature. Activation allows the development of a porous structure of biochar, but significantly increases the cost of the finished product. More often biochar is not activated and is used as a cheap sorbent that does not require regeneration after use and decomposes naturally. The variety of raw materials depends on the climate of the region and the type of production.

Table. Characterisation of biochar from different raw materials

	Pyrolysis temp., °C	Yield, wt. %	Activation	Total pore volume, $cm^3·g^{-1}$	Surface area, $m^2·g^{-1}$	Ref.
Corn cobs	200	71.53	–	0.172	1.87	67
Corn cobs	400	34.40	–	0.147	7.52	
Corn cobs	600	13.04	–	0.147	4.10	
Walnut shell	400	–	–	0.078	74.06	68
Walnut shall	500	–	–	0.150	128.52	
Walnut shall	600	–	–	0.296	488.89	
Walnut shall	700	–	–	0.695	737.98	
Peanut shell	400	36.9	–	0.160	0.20	69
Peanut shell	600	28.2	–	0.516	–	
Peanut shell	800	21.9	–	0.580	–	
Peanut shell	850	12.4	KOH	1.02	2270.5	70
Peanut shell	850	19.3	$ZnCl_2$	0.26	471.4	
Rapesed husk	200	47.14	–	–		71
Rice Husk Char	500	–	–	0.160	34.40	72
Orange peel	200	61.60	–	0.010	–	73
Orange peel	400	30.00	–	0.010	–	
Orange peel	700	22.20	–	0.035	–	
Wheat straw	500	30.00	–	0.041	20.20	74
Spend coffee grounds	500	–	–	0.32	57.2	75
Spend coffee grounds	600	–	–	0.24	30.8	
Oil palm fibers	529	–	–	0.222		76
Food waste	600	30.9	–	–	1.36	77
Food waste + wooden sawdust	600	35.4	–	–	1.83	
Minimum	200	12.4	–	0.01	0.2	–
Maximum	850	71.53	–	1.02	737.98	–

Biochar is often used as a sorbent to purify different liquids. The most popular application of this product is the purification of water and wastewater. Each type of contamination in water treatment requires biochar with specific porosity values. Not only the pore area is important, but also the pore size. Not all types of molecules can adsorb microporous materials[78]. Removal of Cd from water using biochar is an effective method, pyrolysis at 300–900 °C was used to regenerate the material after sorption[79]. Biochar not only treats wastewater but also affects microbial activity, which increases the treatment effect[80]. Moving towards a green economy, non-standard solutions for disinfecting water bodies and blocking decomposition reactions in wetlands are relevant. The use of chemicals in this area causes environmental problems, while biochar decomposes naturally and is an environmentally friendly material[81]. The treatment of antibiotic wastewater is also done with biochar. Residues of medical preparations not only chemically but also in some cases biologically pollute water and despite the search for new treatment methods, the problem is very urgent[82]. However, biochar is also suitable for the purification of chemical liquids, *e. g.* the purification of phosphoric acid[83]. Lactic acid is purified from fermented broth using biochar[84]. Phytochrome is removed using biochar derived from rice straw[85]. Biochar is also suitable for slurry treatment, the particle size distribution of the material is important in this process[86]. As a result of leather, paper, and textile production, large quantities of synthetic dyes pollute wastewater[87]. There are many studies on the sorption properties of biochar with different chemicals, which allow expanding the applications of this material[88]. Big problem with the removal of organic pollutants, research on this topic is very relevant[89]. The presence of biochar in the liquid affects the ionic liquid as shown in the study with wheat[90]. This research is very important for agriculture.

6.2. Gas Treatment

There are types of biochar that are stable N-enriched carbon materials with increased CO_2 absorption from CO_2/CH_4 and CO_2/N_2 gas mixtures[91]. Sewage gases are a big environmental problem for their sorption using biochar[92]. Oxidative modification strategy of nitrogen-doped biochar surface is studied to enhance CO_2 adsorption. Such biochar shows an adsorption activity of 5–8 $mmol \cdot g^{-1}$.[93] Biochar is used to remove NO from flue gases, which suppresses the formation of acidic gases and the purification reaches 100 %[94]. Depending on the application, unactivated and activated biochar as well as biochar with various chemical elements applied on the surface are used for gas purification. Elemental mercury is one of the most difficult contaminants to sorb with biochar[95]. Chemical, metallurgical and even textile industries emit many toxic gases that are cleaned with biochar[96]. The most common and toxic industrial gases are H_2S and SO_2. Since the different binding energies of SO_2 depend on the surface, the adsorption capacity on the biochar is related to their surface function. Nitrogen-containing functional groups such as pyridine-N, pyrrole-N, and pyridone-N on graphite carbon materials have been reported to have a higher adsorption energy of SO_2 compared with functional groups that do not contain N elements. The problem of landfill gases is very urgent and is solved with the use of biochar. Studies have shown that the filters sorbed heavier siloxanes, while the capture of volatile siloxanes and hydrogen was reduced[97]. Various methods are used to improve the quality of biochar, ranging from ultrasonic and microwave treatment to treatment with chemicals. Such lignin-based materials have been investigated for CO_2 capture. As a result of the tests, the specific surface areas of biochar increased by 15 % after treatment, and the CO_2 uptake reached 178.75 $mg \cdot g^{-1}$ after treatment[98].

7. Conclusions

Today, the world produces more than 50 million tons of biochar per year. It can be noted that its use is environmentally and economically promising and has a wide range of applications in various industries. Among the various strategies aimed at reducing greenhouse gas emissions, the use of biomass in coke production as a component of coal charge, in blast furnace smelting and agglomeration, deserves attention. For example, replacing fossil fuels consumed in the metallurgical process with biomass can maintain both the carbon content required for reduction and the energy needed for melting, while reducing greenhouse gas emissions.

The use of biomass, which is a renewable resource, in the production of biocomposites can reduce costs, dependence on fossil sources (plastic and other petroleum products) and negative environmental impact. A significant advantage of biocomposites containing charcoal is their improved mechanical characteristics and resistance to environmental factors.

The ability of biochar to nourish plants with trace elements is another advantage of this product. The use of biochar improves and increases nitrogen assimilation and affects plant growth, helping to reduce soil salinity. Biochar prevents the absorption of heavy metals by plants, positively affecting their growth, development, and plant yield.

Biochar also helps to solve environmental problems caused by human activity and is used as a sorbent for the purification of drinking water, wastewater, and gases.

The effectiveness of the sorption process depends on the physical and chemical properties of the sorbent (specific surface area, pore volume, mechanical strength) and the type of contaminant. Low ash content, minimal volatile yield, developed pore system, and low cost make the use of biochar as a sorbent promising and economically feasible. The use of chemicals in this field creates environmental problems, whereas biochar decomposes naturally and is an environmentally friendly material. Biochar is used for the adsorption of surface-active substances from wastewater. Also, the efficiency of its use for the removal of chromium, copper, lead, and cadmium ions from industrial wastewater was established. The effective use of biochar for the industrial removal of SO_2, NO_x and CO_2 from flue gas streams has been proven.

It is important to research and improve the methods of biomass processing into charcoal, which will make it possible to predict the influence of its physical properties on the structure and obtain fuel with a set of characteristics depending on the application field.

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СУЧАСНІ НАПРЯМИ ВИКОРИСТАННЯ БІОПАЛИВА В РІЗНИХ ТЕХНОЛОГІЯХ І ГАЛУЗЯХ ПРОМИСЛОВОСТІ. ОГЛЯД

Анотація. *Проаналізовано використання деревного вугілля для різних галузей промисловості (як сорбенту, палива, відновника в металургійній промисловості, компонента вугільних шихт коксування, біокомпозитів, модифікації вибухових речовин тощо). Зазначено, що напрям використання залежить від якості та характеристик деревного вугілля (розмір, фізичні властивості, хімічний склад), які обумовлені природою сировини (деревина або відходи сільського господарства), її хімічним складом, температурою карбонізації.*

Ключові слова: *деревне вугілля, паливо, металургійна технологія, біокомпозити, модифікація вибухових речовин, деревне вугілля в сільському господарстві, сорбент.*