www.ees.uni.opole.pl
ISSN paper version 1642-2597
ISSN electronic version 2081-8319
Economic and Environmental Studies
Vol. 17, No. 3 (43/2017), 597-611, September 2017

Application of the Biochar-Based Technologies as the Way of Realization of the Sustainable Development Strategy

Daria GĄSIOR*
Opole University of Technology, Faculty of Mechanical Engineering, Department of Environmental Engineering, Poland

Wilhelm Jan TIC
Opole University of Technology, Faculty of Mechanical Engineering, Department of Environmental Engineering, Poland

Abstract: The technologies of thermal processing of biomass, biowaste or sewage sludge into biochar as well as its potential use in the industry, power industry, housebuilding industry, agriculture or environmental protection attract growing attention. The multi-faceted, unique properties of biochar make it particularly attractive from the point of view of the achievement of sustainable development goals according to which the needs of the present generation should be satisfied in such a way so as not to harm the environment and in such a way that the future generations could use the same natural environment as we do. The EU policy focusing on the implementation of the principles of sustainable development emphasises the need to reduce the exploitation of natural resources, to use effective technologies processing waste and to develop new biodegradable and environmentally friendly products.
Due to the wide range of biochar applications in many economy sectors, the ways of production, ensuring the reduction of waste generation, and its economic attractiveness, this product meets the expectations of the sustainable development policy. The aim of this paper is review the biochar-based technologies and the concepts of its application, and description of the disadvantages and advantages each of them..

Keywords: sustainable development, biochar, reducing of CO_2 emission, thermal processing of biomass

JEL codes: Q530, Q200

https://doi.org/10.25167/ees.2017.43.9

Correspondence Address: Daria Gąsior, Opole University of Technology, Faculty of Mechanical Engineering, Department of Environmental Engineering, Poland, ul. St. Mikołajczyka 5, Opole, Poland. Tel.: 503421999 Fax: 077/ 4499923 E-mail: gasiordaria@gmail.com
*Author is also an employee of the Institute of Ceramics and Building Materials in Warsaw, Building Materials Engineering Division in Opole

1. Introduction

Owing to greenhouse emissions and the intensification of environmental pollution, new, more environmentally-friendly solutions are required so as to minimize environmental hazards. The problem of environmental pollution has for some time been a focus of interest in the scientific circles and businesses due to the growing awareness of the adverse impact of manufacturing on ecological balance. The ultimate problem has become to obtain the appropriate tools enabling the problems to be solved in compliance with the principles of sustainable development. The idea is based on the theory that social, economic and pro-ecological objectives are of equal importance and choosing just one of these areas as a center of attention or limiting any one them will be detrimental to the quality of life of the present and future generations.

In the recent decades, such problems as soil degradation, biodegradable waste disposal, carbon sequestration in the soil, reduction of greenhouse emissions, the necessity to limit the use of artificial fertilizers and plant pesticides, have become rather tough.

These environmental problems have a potential solution in the form biochar, renewable solid fuel obtained by biomass pyrolysis. By the suitable processing of energy plants, agricultural, silvicultural, horticultural or food-processing waste, or even manure, the material is rendered suitable for reuse. This helps reduce the volume of waste which is disposed of by dumping and comply with the principle of sustainable development – an essential component of environmental policy in the EU member states, including Poland. Biochar from pyrolysis is in the form of fine-grained, carbon-rich, porous solids. It is obtained in the absence of oxygen by pyrolysis from biomass and vegetable waste. In addition to the solid product, the process provides a number of highly calorific liquid and gaseous products. As a result of pyrolysis in the absence of oxygen, the chemical properties of the carbon constituent of biomass are modified, rendering a carbon-rich product with an improved resistance to microbial degradation in comparison with the initial material.

The efficiency of pyrolysis, defined as the biochar yield per cent of the final product, depends mainly by the processing conditions: heating rate, decomposition time, temperature and pressure. Examples of efficiency data for pyrolysis, depending on the processing condition, are shown in table 1.

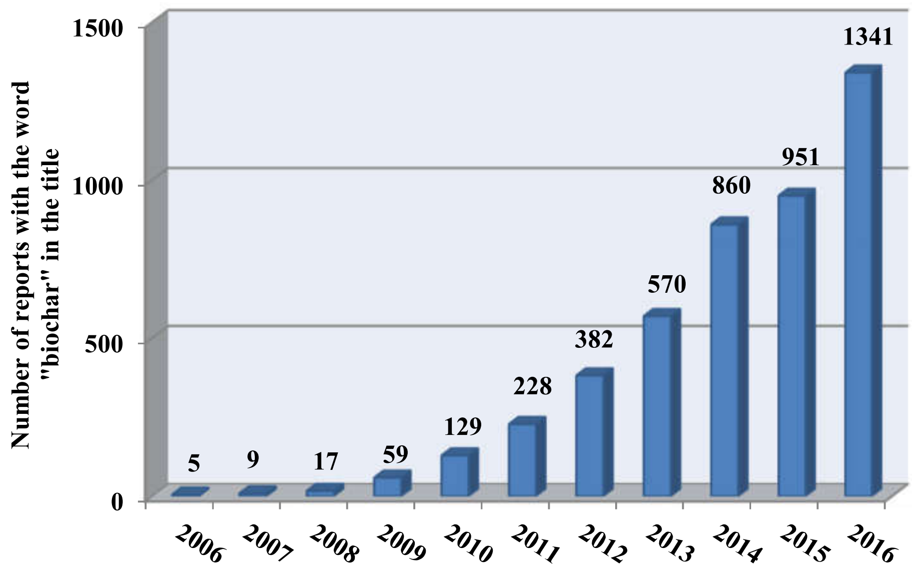
Table 1. Effect of pyrolysis process conditions and type of raw material on biochar yields

Starting material for biochar production	Pyrolysis process conditions		Biochar percentage in process products, %
	Temperature, ºC	Time, min	
wood	300	10	89,8
		60	43,7
	750	10	23,0
		60	22,7
straw	300	10	94,8
		60	36,8
	750	10	23,7
		60	24,4
Green waste	300	10	98,4
		60	48,6
	750	10	26,4
		60	23,7

Source: Ronsse et al., 2013: 104.

The recent decade has seen a more lively interest in biochar after it was rediscovered as a product with high potential in many industries due to its environmentally friendly nature (figure 1).

Figure 1. Growing interest in biochar over the last decade (2006-2016)



Source: Author's own elaboration based on: Scientific database Scopus, 2017.

The incineration of biochar is the answer to one of the strategic objectives of sustainable development: it shows a zero balance of CO_2 emissions and the simultaneous increase in the efficiency of production of electric energy and heat.

In agriculture and horticulture, biochar is successfully used for soil amendment, contributing to better crop yields. Animal feeds with added biochar are known to cause certain desirable phenomena in animal breeding, for instance, lower death rates, better control of disagreeable smells in the animal breeding facilities, and higher levels of proteins and fats in cattle milk.

Owing to its low-emission nature and high energy potential, biochar is an attractive alternative to the presently used fossil fuels. More and more interest is observed also in the use of biochar in the construction industry. The material has excellent absorption properties according to a number of reports, which enable its use in water filtering, or adsorbents for the purification of liquid waste or exhaust gases.

The objective of this paper is to review the high potential of biochar in a number of applications as well as the various methods of its modification (by processing or activation) to improve its properties, as required for a specific purpose.

2. The use of biochar in the power industry

One of the major applications of biochar is as a renewable fuel. Biochar from quality biomass has a high calorific value (25 MJ/kg). This renders its useful in the power industry as an alternative to the presently used fossil fuels (Bubel and Rogosz, 2014). The material has a zero balance of CO_2 emissions, which is desirable in materials used as in firing or co-firing processes in power plants and in heat-and-power plants. The properties of biochar which are of interest to the power industry include: calorific value, contents of carbon, moisture, ash and volatiles. The parameters depend on such factors as: type of raw materials for biochar production and process conditions of pyrolysis. Table 2 shows the examples of such parameters, which characterize fossil fuels, biomass of various origins, and biochars obtained from those kinds of biomass. High calorific value which is typical of biochar, as well as its low emission nature, contribute to its particularly high potential as a renewable fuel in the future of the power industry.

Table 2. Parameters of selected fuels, biomasses, and biochars obtained by biomass pyrolysis

Fuel	Calorific value, MJ/kg	Moisture, %	Carbon, %	Ash, %	Volatiles, %
Fossil fuels					
Coal	32-35	1-18	75-96	12	1-45
Charcoal	24-31	10-70	58-78	10-20	45-65
Natural gas	48	-	86	0	-
Peat	21-24	70-90	56-62	-	62-70
Biomass					
Oil palm fruit waste	17,1	2,4	53,8	3,1	81,9
Saw dust	19,6	6,2	41,7	1,2	69,9
Apricot kernel shells	19,3	-	-	1,4	77,1
Chestnut shells	15,5	-	-	1,6	69,7
Grape seeds	20,5	-	-	7,5	70,5
Cellulose	16,5	-	43,0	0,5	93,4
Biochar					
Biochar from saw dust	28,5	2,9	84,9	3,0	42,5
Biochar from oil palm fruit waste	23,0	-	68,6	-	-
Biochar from apricot kernel shells	30,8	-	-	8,5	19,8
Biochar from chestnut shells	25,9	-	-	5,4	34,3
Biochar from grape seeds	26,7	-	-	9,6	39,5
Biochar from cellulose	27,7	-	76,5	2,7	42,2

Source: Bartuś, 2003; Sukiran et al., 2011:984; Mazlan et al., 2015:1; Ozçimen, and Ersoy-Meriçboyu, 2010:1319; Kim et al., 2015:14040.

3. Biochar as a soil amendment

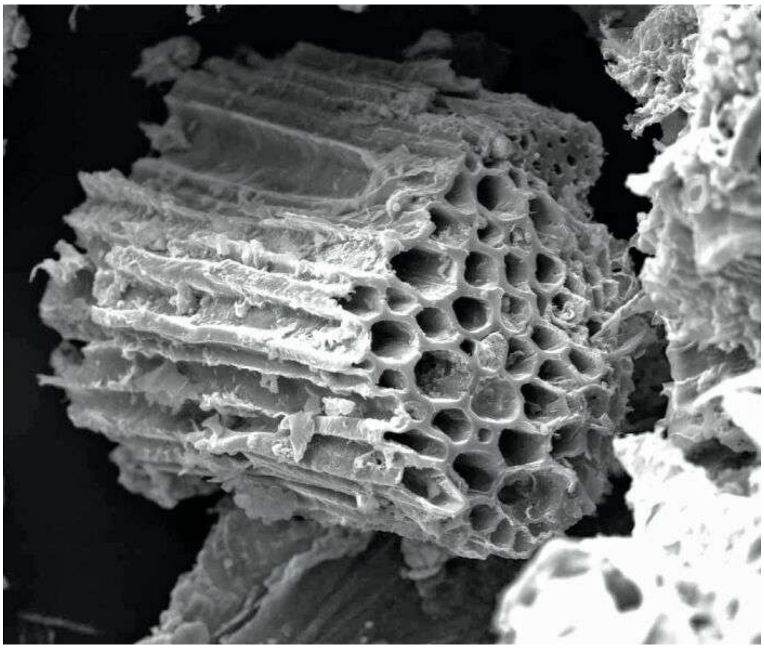
There are literature reports on the characteristics and quality of agricultural soils that most of them have lost an alarming 30-75% of organic carbon, in comparison with the soils of "before" the era of artificial fertilization (Vaccari et al., 2011: 231). One of the ways to restore natural balance in soils and supplement for their loss of nutrients is to fertilize the soils by biochar addition (Gładki J., 2017). The growth of interest in biochar as an additive to soils can be linked to the discovery of the unique, desirable characteristics of the Amazon *terra preta* (Indian dark earth). Studies on the soil properties indicate that soils in the area have a rich mineral composition as the result of agrotechnical treatments by pre-Columbian Indian tribes. Such treatments consisted in soil fertilization by means of charcoal, which has comparable properties to that of biochar. The Indian tribes lived in the Amazon area between 450 BC to 950 AD (Nanda et al., 2016: 201).

Other studies have confirmed that adding biochar to soils improves their physicochemical and biological properties, which results in better crop yields (Graber et al., 2010:481; Atkinson et al., 2010:1). Biochar has a beneficial impact on soils because of its high chemical reactivity in relation to organic and inorganic compounds such as toxic PAH, PCB, plant pesticides or heavy metals which are less readily bioavailable to plants after being fixed by biochar (Medyńska-Juraszek, 2016:151; Inyang et al., 2012:50).

Verheijen (2010) reported that the addition of biochar fertilizes the soil, has an impact on carbon sequestration and reduces emissions from soil surfaces of nitrogen oxides and methane originating from natural putrefaction processes taking place in the soil. Both methane and N_2O are classified as harmful greenhouse gases with a much higher greenhouse potential than that of CO_2.

Soils have a significant content of natural carbon originating from biomass decomposition. It is a highly unstable material, released into the atmosphere as a result of cultivating treatments or temperature increase. Owing to its ability to fix organic carbon forming stable structures, biochar reduces CO_2 emissions into the atmosphere to improve CO_2 sequestration in the soils (Lehmann, 2011: 1812). The fertilization properties of biochar as a soil additive are very poor. The disadvantage is caused by the chemical composition of the starting materials used in its production: the materials are typically poor in nutrients or such nutrients are not readily bioavailable (Medyńska-Juraszek, 2016:151). However, having a highly porous structure, biochar has the capacity to store macro- and microelements in the soil. The capacity of biochar to exchange the substances helps increase their uptake by plants and reduces the risk of their elution and transport into surface and underground waters (Laird, 2008: 178). The ion-exchange capacity of biochar depends on the temperature of pyrolysis: the product has increasingly lower ion-exchange capacities above 600^{o}C (Lehman, 2007:381). The use of biochar as a soil amendment is greatly facilitated by its highly porous structure: it facilitates microbial growth, thus improving fertility. Moreover, the water retention capacity of soils is improved by the high porosity and high specific surface of biochar (Abel, 2013:183). Figure 2 shows the porous structure of biochar particles. The image was obtained by means of scanning electron microscopy (SEM).

Figure 2. Image of porous structure of biochar, obtained by SEM



Source: McLaughlin and Pyle, 2016.

Numerous reports also associate soil amendment with its alkaline pH. Biochars obtained in high-temperature processes (450-800^{o}C) are characterized by high alkalinity because inorganic carbonates, such as $CaCO_3$ and $MgCO_3$, are formed. Alkalization by introduction into the soil of biochar is directly proportional to the biochar dosage (Medyńska-Juraszek, 2016:151).

Apart from the different advantages of the use of biochar as a soil amendment, there are also some limitations to its use for the purpose. Its major disadvantage is the potential presence of toxic, carcinogenic and mutagenic compounds (PAH, dioxins, furans) resulting from the high-temperatures processing of materials to obtain biochar. Even though biochar has numerous advantages in soil amendment applications, it ought to be noted that its composition and behavior in the soil environment will vary according to the type of starting materials for its production and the processing conditions. This area of the application of biochar is worth investigating for the better understanding of certain details, and experimental studies ought to be continued with a view to the safe using of biochar as a promising alternative to organic and inorganic fertilizers and plant pesticides.

4. The properties of biochar which are desirable in the construction industry

Studies being carried out in the Ithaca Institute recently were focused on the use of biochar as a construction material (Schmidt, 2013). Owing to its excellent insulating properties, biochar is known to improve air quality, absorb moisture and even protect from electromagnetic radiation. The material has a high specific surface (>300m^2/g). Thanks to the presence of nano-, micro- and mesopores in it, biochar is an excellent water retaining material, therefore, it may be used as an insulating material and for moisture control, for instance in residential spaces. It is able to absorb water weights as high as fives times its own. Moreover, biochar has a very low thermal conductivity. These properties make it an excellent component of plastering mortars. It can be added to gypsum together with clay, lime or cement mortar. A biochar-clay mortar consists of 50% biochar, 30% suitable sand fraction, and 20% clay. A layer of the plaster will dry as fast as gypsum plasters. Further layers can be applied as soon as after the lapse of 12h. (Schmidt, 2014). Owing to its porous structure, biochar is able to absorb unpleasant smells and toxins in addition to moisture, which is of great importance, for instance, in smoking areas (Gładki, 2017). Despite their excellent moisture- and thermal insulating properties, biochar-based plasters do not obstruct air exchange in rooms regardless of the season of the year. Such plasters are also useful for outdoor applications on the walls. They are a good alternative to foamed polystyrene – the most popular building insulating material.

After being combined with lime, biochar can be applied on outdoor walls by the so-called "pressure-spraying technique". Buildings which have been provided with this type of insulation, absorb harmful volatile compounds while providing a healthy indoor environment.

Studies are in progress on the use of biochar for the production of brick or concrete (Schmidt, 2014). The idea behind these light, biochar-based concretes is to entirely eliminate sand from the concrete composition. The product is a light concrete with densities of approx. 1.2 g/cm^3. The results of pilot studies indicate that samples of biochar-based concrete have densities of 1 g/cm^3 or lower and compressive strengths of roughly 20MPa, which indicates high potential for construction and highway-engineering applications.

5. Biochar as a precursor in activated carbon production

Scientific literature on the applicability of biochar indicates a growing interest in the applicability of biochar as a precursor in activated carbon production.

Activated carbons are defined as carbon materials with a strongly developed specific surface and high porosity, which render them particularly suitable for the adsorption of chemicals from gases and liquids. They are a group of materials of which the usefulness is highly diverse and growing.

A review of international and domestic literature on the subject indicates a great interest in the application of activated carbons in various fields, for instance, in the purification of gases (Liu et al., 2013:2165-2172; Jiang et al., 2012:1862; Ren et al., 2006: 25) or water (Lompe et al., 2016:42; Dabioch et al., 2013:742; Spahis. A. et al., 2008:519), as a catalyst or catalyst carrier in the chemical industry (Lam et al., 2016:1; Lu et al., 2016:10618), in pharmaceutical or medical applications (Ying-Ying et al., 2016:613; Swapna Priya et al., 2015: 42) and in broadly-understood environmental protection (Oghenejoboh et al., 2016:52; Kołtowski et al., 2016:11058).

The prospective uses of biochar in the chemical industry include the elimination of sulfur dioxide and nitrogen oxides from exhaust gases (Rashidi et al., 2015: 1507; Athappan et al., 2015:2502). It is estimated that the global production of all kinds of activated carbons is now roughly 1 mln t/y and still growing at a rate of some 5-7% a year (Borowiecki, 2008).

Activated carbon production is based on natural organic feedstocks having a polymeric structure. Materials used in a mass scale for the purpose include wood (35% in the overall use of raw materials), coal (28%), charcoal (14%), or peat (10%) (Borowiecki, 2008).

Synthetic polymers, such as waste phenol-formaldehyde resins, polyfurfuryl alcohol, polyvinylidene chloride (3%) are much more attractive and expensive as a feedstock. Purchasing conventional materials for activated carbon production usually accounts for high expenses.

New, low-cost solutions, which satisfy the sustainable development requirements applicable to alternative raw materials, are sought so that the costs of activated carbon production can be reduced. Biochar is a possible answer to that requirement of the market. On the other hand, for biochar to successfully compete with active carbon in the aspect of its properties, it must be activated beforehand. Depending on the activating factor, the process may involve either physical or chemical activation.

Even though physical activation of biochar seems to be able to affect its physical properties, including porosity, specific surface, etc., studies indicate also a significant impact on the chemical structure of its surface (for instance, the presence of surface functional groups, hydrophobicity, polarity). The physical activation of biochar is typically carried out with the use of steam and carbon dioxide.

The major benefits of physical activation with steam include the elimination of the volatile constituents of biochar, formation of new micropores in the structure, and expansion of the existing ones. Lima et al. (2010:1515) describes a study on the activation of biochars obtained by the rapid pyrolysis of biomass in the form of assorted plant-based waste. Activation was carried out at an atmospheric pressure at a temperature of 800°C for 45 minutes. A significant increase in porosity was observed for biochar in addition to a dramatic difference in the value of specific surface from a negligible range of 0-4.6 m^2g^{-1} to as much as 793 m^2g^{-1}. Rajapaksha et al. (2016:2081) also reported significantly improved surface properties of biochar after its physical activation with steam for 45 minutes. Biochar, obtained by heating waste tea at 700°C, after treatment with steam was characterized by much higher specific surfaces (the value increased from 342 to 576 m^2g^{-1}), pore volume (increased from 0.022 to 0.109 cm^3g^{-1}), pore diameter (increased from 1.756 to 1.998 nm), in comparison with the untreated biochar sample. In the continuation of studies on the biochar, it was found that activation with steam resulted in a much reduced surface hydrophobicity of biochar and an improved polarity.

Zhang et al., (2014:279) observed a higher quantity of surface oxygen groups (-COOH, -OH) after the physical activation of biochar surface with steam.

The physical surface activation of carbon by means of gases (CO_2, N_2, NH_3, air, O_2) or gas mixtures is becoming a more and more frequently used technique. Gao et al. (2016:24906) described a process of activation with carbon dioxide (temperatures in the range 600-900°C, for 1 and 2 h) of hickory wood and peanut hulls. It was observed that active surface and pore volume of biochar were increasing with increase in temperature and time of activation.

Biochar from cotton stalks was activated using a mixture of gases composed of carbon dioxide and ammonia, at a temperature of 500-900°C; high specific surfaces of 627 m^2g^{-1} were obtained, in comparison with 224 m^2g^{-1} for the non-activated biochar, as reported by Zhang et al. (2014:20). The process was accompanied by the introduction of surface functional groups with N into the biochar structure.

The various agents used in the chemical surface activation of biochar include mainly acids (HCl, HNO_3, H_2SO_4, H_3PO_4), bases (KOH, NaOH), and oxidizing agents (H_2O_2, $KMnO_4$). The positive effect of chemical activation on the surface properties of biochar is confirmed in literature reports. Mahmoud et al. (2012:449) reported the chemical activation of biochar obtained from hickory fiber. The activation process provided a product with a much higher specific surface (increase from 289.5 to 346.6 m^2g^{-1}). The SEM image of the activated biochar indicates the presence of a large quantity of pores in the biochar structure. The pores had the characteristic honeycomb shape.

Using KOH for the activation of biochar provided higher specific surfaces from 14 to 1277 m^2 and larger micropore volumes to 0.4952 cm^2g^{-1} (Angına et al., 2013:705). The use of hydrogen peroxide as the oxidizing agent in the activation of biochar obtained from peanut shells resulted in higher oxygen functional groups on the biochar surface, although such activation did not render any increase in specific surface (Xuea et al., 2012:673).

Analyses of the available reports of studies on the effect of activation on the surface properties of biochars indicate that technology of biochar production can successfully replace or support the existing activated carbon production technologies as a cost-effective and environmentally-friendly, a potential alternative.

6. Conclusion

The diverse possible uses of biochar satisfy the requirements of sustainable development. The very process of biochar production from biodegradable waste helps reduce the volume of waste which is at present disposed of by dumping and also is a means to recover energy, providing measurable benefits to the economy and the environment.

Biochar has advantageous properties – such as high content of organic carbon, high porosity, and well developed specific surface – which make it applicable, for instance, as a renewable fuel in the power industry, material enabling carbon sequestration, constituent of organic fertilizers amending agricultural soils, as an adsorbent of contaminants from the aqueous environment (water, waste water) and gases (exhaust and process gases).

Only some of the possible uses of biochar are presented in this paper. A review of 55 of its possible applications was made by Hans Peter Schmidt in The Biochar Journal in 2014 (Schmidt and Wilson, 2014), and studies of the material are in progress. In the recent years, considerable interest in biochar has been observed also in the metallurgic, electronic, chemical, textile, and pharmaceutical industries.

The list of biochar-based products which are already on the global market includes: microbiological preparations, supplements in animal feeds, components of paints and dyes, semi-conductors and batteries, components of cosmetics and pharmaceuticals, food preservatives, additives to textiles for use in the production of functional clothes, filling materials for pillows and mattresses (Malińska K., 2014:36).

The prospective uses of biochar are extremely promising, yet, a comprehensive analysis of the product ought to include a discussion of its disadvantages and this aspect is omitted in most papers. The use of the potential of biochar in the global scale involves the necessity to incessantly provide the substrates (mainly biomass) for its production. An intensively obtained biomass – for instance from the cultivation of energy plants – will involve a considerable exploitation of soils, thereby affecting their properties and depleting the soils as the result.

It is worth noting that the choice of substrates for biochar production as well as its processing parameters (by pyrolysis), ought to be governed by the target physico-chemical properties of the final product. Needless to say, this depends on its potential function. Therefore, focus in research and development works ought to be on the full understanding of the physico-chemical properties of biochars obtained from various raw materials and on the clarification of the processes and mechanisms of its interactions with natural environment in the time perspective. Biochar has a number of advantages characterizing it as a sustainable material but, speaking of its darker side, it potentially carries hazardous substances such as PAH, dioxins, furans, and heavy metals. The content of such hazardous constituents in biochar largely depends on the type of raw material used for its production.

Further studies on biochar necessitate not only a technical description of its properties but also a cost-efficiency analysis, intended to assess its production cost. Moreover, it seems desirable to develop a system of the classification of biochars in the aspect of raw materials and processing parameters, taking into account their physico-chemical properties and areas of potential us.

Literature

Abel, S.; Peters, A.; Trinks, S.; Schonsky, H.; Facklam, M.; Wessolek, G. (2013). Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. *Geoderma* 202-203: 183–191.

Angına, D.; Köse, T.E.; Selengil, U. (2013). Production and characterization of activated carbon prepared from safflower seed cake biochar and its ability to absorb reactive dyestuff. *Applied Surface Science* 280: 705-710.

Athappan, A.; Sattler, M.L.; Sethupathi, S. (2015). Selective catalytic reduction of nitric oxide over cerium-doped activated carbons. *Journal of Environmental Chemical Engineering* 3(4): 2502-2513.

Atkinson, C.J.; Fitzgerald, J.D.; Hipps, N.A. (2010). Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. *Plant Soil* 337: 1–18.

Bartuś, T. (2003). Parametry chemiczno - technologiczne i oparte na nich klasyfikacje węgli brunatnych. Available at: http://home.agh.edu.pl/~bartus/efekty_docs/parametry_wegla_dzia%B3alnosc_statutowa_2003-2004.doc Accessed 4 April 2017.

Borowiecki, T.; Kijeński J.; Machnikowski, J.; Ściążko, M. (2008). *Czysta energia, produkty chemiczne i paliwa z węgla – ocena potencjału rozwojowego*. Zabrze: IChPW.

Bubel, F.; Rogosz, B. (2014). *Biowęgiel – Właściwości i zastosowanie*. Available at: http://globenergia.pl/biowegiel-wlasciwosci-i-zastosowanie. Accessed 4 April 2017.

Dabioch, M.; Skorek, R.; Kita, A.; Janoska, P.; Pytlakowska, K.; Zerzucha, P.; Sitko, R. (2013). A study on adsorption of metals by activated carbon in a large-scale (municipal) process of surface water purification. *Central European Journal of Chemistry* 11(5): 742-753.

Gao, J.F.B.; Zimmerman, A.R.; Ro, K.S.; Chen, J. (2016). Physically (CO_2) activated hydrochars from hickory and peanut hull: Preparation, characterization, and sorption of methylene blue, lead, copper, and cadmium. *Royal Society of Chemistry* 6: 24906–24911.

Gładki, J. (2017). *Biowęgiel szansą dla zrównoważonego rozwoju*. Sędziszów: Oficyna Poligraficzna Apla Sp.J.

Graber, E.R.;, Harel, Y.M.; Kolton, M.; Cytryn, E.; Silber, A.; David, D.R.; Tsechansky, L.; Borenshtein, M.; Elad, Y. (2010). Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. *Plant Soil* 337: 481–496.

Inyang, M.; Gao, B.; Yao, Y.; Xue, Y.; Zimmerman, A.; Pullammanappallil, P.; Cao, X. (2012). Removal of heavy metals from aqueous solution by biochars derived from anaerobically digested biomass. *Bioresource Technology* 110: 50-56.

Jiang, M.; Ning, P.; Wang, Z.H.; Bai, Y.W.; Chen W.;, Zhang W.; Wang R.B. (2012). Preparation and adsorption property of modified activated carbon for purification of HCN in closed carbide furnace tail gas. *Advanced Materials Research* 476-478: 1862-1866.

Kim, D.; Yoshikawa, K..; Park, K-Y. (2015). Characteristics of biochar obtained by hydrothermal carbonization of cellulose for renewable energy. *Energies* 8: 14040-14048.

Kołtowski, M.; Hilber, I.; Bucheli, T.D.; Oleszczuk, P. (2016). Effect of activated carbon and biochars on the bioavailability of polycyclic aromatic hydrocarbons in different industrially contaminated soils. *Environmental Science and Pollution Research* 23(11): 11058-11068.

Laird D. (2008). The charcoal vision: A win-win-win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agronomy Journal* 100: 178-181.

Lam, S.S.; Liew, R.K.; Wong, Y.M.; Azwar, E.; Jusoh. A.; Wahi, R. (2016). Activated carbon for catalyst support from microwave pyrolysis of orange peel. *Waste and Biomass Valorization*: 1-11.

Lehman, J. (2007). Bio-energy in the black. *Frontiers in Ecology and the Environment* 5(7): 381-387.

Lehmann, J.; Rillig, M.; Thies, J.; Masiello, C.; Hockaday, W.; Crowley, D. (2011). Biochar effects on soil biota – A review. *Soil Biology and Biochemistry* 43(9): 1812-1836.

Lima, I.M.; Boateng, A.A.; Klasson, K.T. (2010). Physicochemical and adsorptive propertiesof fast-pyrolysis bio-chars and their steam activated counterparts. Chemical Technology and Biotechnology 85(11): 1515-1521.

Liu, W.; Wang, X.; Ning, P.; Chen, W.; Qiu, J.; Zhou, Y. (2013). Adsorptive purification of C4H4S in industrial waste gas by Cu-based modified activated carbon. *Journal of Central South University (Science and Technology)* 44(5): 2165-2172.

Lompe, K.M.; Menard D.; Barbeau, B. (2016). Performance of biological magnetic powdered activated carbon for drinking water purification. *Water Research* 96: 42-51.

Lu, Q.; Ye, X.; Zhang, Z.; Cui, M.S.; Guo, H.; Qi, W.; Dong, Ch.; Yang, Y. (2016). Catalytic fast pyrolysis of bagasse using activated carbon catalyst to selectively produce 4-ethyl phenol. *Energy and Fuels* 30(12): 10618-10626.

Mahmoud, D.K.; Salleh, M.A.M.; Karim, W.A.W.A.; Idris, A.; Abidin, Z.Z. (2012). Batch adsorption of basic dye using acid treated kenaf fibre char: Equilibrium, kinetic and thermodynamic studies. *Chemical Engineering Journal* 181-182: 449-457.

Malińska, K. (2014). Biowęgiel dla środowiska i nie tylko. *Chemia Przemysłowa* 3: 36-39.

Mazlan, M.A.F.; Uemura, Y.; Osman, N.B.; Yusup, S. (2015). Characterizations of Bio-char from Fast Pyrolysis of Meranti Wood Sawdust. *Journal of Physics: Conference Series* 622: 1-7.

McLaughlin, H.; Pyle, K. (2016). *Practical applications of biochar in the landscape*. Available at: http://www.ecolandscaping.org/04/biochar/practical-applications-of-biochar-in-the-landscape/. Accessed 7 April 2017.

Medyńska-Juraszek, A. (2016). Biowęgiel jako dodatek do gleb. *Soil Science Annual* 67(3): 151-157.

Nanda, S.; Dalai, A.K.; Berruti, F.; Kozinski, J.A.. (2016). Biochar as an exceptional bioresource for energy, agronomy, carbon sequestration, activated carbon and specialty materials. *Vaste Biomass Valor* 7: 201-235.

Oghenejoboh, K.M.; Otuagoma, S.O.; Ohimor, E.O. (2016). Application of cassava peels activated carbon in the treatment of oil refinery wastewater - a comparative analysis. *Journal of Ecological Engineering* 17(2): 52-58.

Ozçimen, D.; Ersoy-Meriçboyu, A. (2010). Characterization of biochar and bio-oil samples obtained from carbonization of various biomass materials. *Renewable Energy* 35: 1319-1324.

Rajapaksha, A.U.; Vithanage, M.; Lee, S.S.; Seo, D-Ch.; Tsang, D.C.W.; Ok, Y.S. (2016). Steam activation of biochars facilitates kinetics and pH-resilience of sulfamethazine sorption. *Journal of Soils and Sediments* 16(8): 2081-2089.

Rashidi, N.A.;, Yusup, S. (2015). Effect of process variables on the production of biomass-based activated carbons for carbon dioxide capture and sequestration. *Chemical Engineering Transactions* 45: 1507-1512.

Ren, Z.-D.; Chen, L.; Ning, P. (2006). Progress in purification of PH3, H2S in yellow phosphorus tail gas with activated carbon. *Modern Chemical Industry* 26(11): 25-28.

Ronsse, F.; Van Hecke, S.; Dickinson, D.; Prins, W. (2013). Production and characterization of slow pyrolysis biochar: influence of feedstock type and pyrolysis conditions. *GCB Bioenergy* 5: 104-115.

Schmidt H.P. (2014). The use of biochar as building material. *The Biochar Journal*. Available at: https://www.biochar-journal.org/en/ct/3-The-use-of-biochar-as-building-material-. Accessed 11 April 2017.

Schmidt, H.P. (2013). The use of biochar as building material - cities as carbon sinks. *Journal for terrior-wine and biodiversity*. Available at: http://www.ithaka-journal.net/pflanzenkohle-zum-hauser-bauen-stadte-als-kohlenstoffsenken?lang=en. Accessed 11 April 2017.

Schmidt, HP; Wilson K. (2014). The 55 uses of biochar. *The Biochar Journal*. Available at: https://www.biochar-journal.org/en/ct/2. Accessed 8 April 2017.

Scientific database Scopus. Available at: https://www.elsevier.com/solutions/scopus. Accessed 4 April 2017.

Spahis, N.; Addoun, A.; Mahmoudi, H.; Ghaffour, N. (2008). Purification of water by activated carbon prepared from olive Stones. *Desalination* 222(1-3): 519-527.

Sukiran, M.A.; Kheang, L.S.; Baker, N.A.; May, C.Y. (2011). Production and characterization of biochar from the pyrolysis of empty fruit bunches. *American Journal of Applied Sciences* 8(10): 984-988.

Swapna Priya, S.; Radha, K.V. (2015). Equilibrium, isotherm, kinetic and thermodynamic adsorption studies of tetracycline hydrochloride onto commercial grade granular activated carbon. *International Journal of Pharmacy and Pharmaceutical Sciences* 7(1): 42-51.

Vaccari, F.P.; Baront,i S.; Lugato, E.; Genesio, L.; Castaldi, S.; Fornasier, F.; Miglietta, F. (2011). Biochar as a strategy to sequester carbon and increase yield in durum wheat. *European Journal of Agronomy* 34: 231-238.

Verheijen, F.; Jeffery, S.; Bastos, C.; Van Der Velde, M.; Diafas, I. (2010). JRC *Scientific and technical Report: Biochar Application to Soils*. Available at: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC55799/jrc_biochar_soils.pdf. Accessed 11 April 2017.

Xuea, Y.; Gao, B.; Yao, Y.; Inyang, M.; Zhang, M.; Zimmerman, A.R.; Ro, K.S. (2012). Hydrogen peroxide modification enhances the ability of biochar (hydrochar) produced from hydrothermal carbonization of peanut hull to remove aqueous heavy metals: Batch and column tests. *Chemical Engineering Journal* 200-202: 673-680.

Ying-Ying, W.; Zhen-Hu, X. (2016). Multi-walled carbon nanotubes and powder-activated carbon adsorbents for the removal of nitrofurazone from aqueous solution. *Journal of Dispersion Science and Technology* 37(5): 613-624.

Zhang, X.; Zhang, S.; Yang, H.; Feng, Y.; Chen, Y.; Wang, X.; Chen, H. (2014). Nitrogen enriched biochar modified by high temperature CO2–ammonia treatment: Characterization and adsorption of CO2. *Chemical Engineering Journal* 257: 20-27.

Zhang, Y.-J.; Xing, Z.-J.; Duan, Z.-K.; Li, M.; Wang, Y. (2014). Effects of steam activation on the pore structure and surface chemistry of activated carbon derived from bamboo waste. *Applied Surface Science* 315(1): 279-286.

Zastosowanie technologii bazujących na wykorzystaniu biowęgla drogą do realizacji założeń zrównoważonego rozwoju

Streszczenie

Technologie termicznego przetwarzania biomasy, bioodpadów czy osadów ściekowych na biowęgiel, podobnie jak jego potencjalne wykorzystanie w przemyśle, energetyce, budownictwie, rolnictwie czy ochronie środowiska budzą coraz większe zainteresowanie. Wieloaspektowe, cenne właściwości biowęgla powodują, że jest on szczególnie atrakcyjnym produktem z punktu widzenia realizacji założeń zrównoważonego rozwoju, w myśl których należy w taki sposób zaspokajać potrzeby obecnego pokolenia by nie szkodzić środowisku oraz aby przyszłe pokolenia mogły korzystać z takiego środowiska naturalnego jakim dysponujemy obecnie. Polityka UE, skupiająca się na realizacji założeń zrównoważonego rozwoju podkreśla konieczność ograniczenia wydobycia surowców naturalnych, stosowania efektywnych technologii przetwarzających odpady oraz opracowania nowych produktów biodegradowalnych, przyjaznych dla środowiska. Zarówno szerokie możliwości wykorzystania biowęgla w wielu gałęziach gospodarki, sposób uzyskania zapewniający redukcję generowanych odpadów, jak i jego atrakcyjność ekonomiczna powodują, że jest to produkt spełniający oczekiwania polityki zrównoważonego rozwoju. Celem pracy jest dokonanie przeglądu technologii opierających się na wykorzystaniu biowęgla oraz koncepcji jego zastosowania wraz z opisem wad oraz zalet każdej z nich.

Słowa kluczowe: zrównoważony rozwój, biowęgiel, ograniczenie emisji CO_2, termiczne przetwarzanie biomasy.