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Analysis of the Use of Biochar from Organic Waste Pyrolysis in Agriculture and Environmental Protection

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ABSTRACT
Nowadays, research on the use of pyrolysis products in the broadly understood economy is widely conducted in the world. This publication presents the results of research on the use of biochar primarily as a material for use in agriculture and environmental protection. In particular, its use to improve soil properties and as a component of organic fertilisers or composts, as well as an ingredient for animal bedding in livestock buildings or an additive for silage is discussed. In addition, the possibilities of using biochar in the energy sector as a solid fuel and in the broader field of environmental protection for remediation of contaminated land, for carbon sequestration and as a raw material for the production of activated carbons are discussed.

Keywords: biochar, pyrolysis, carbon, soil, resource recovery.

INTRODUCTION

The pyrolysis of organic waste is increasingly becoming one of the important elements of the modern closed loop economy. By appropriately controlling the pyrolysis process, different quantitative proportions of the final products can be obtained. Among the pyrolysis products, biochar has particular potential for use in agriculture and environmental protection due to its special physical and chemical properties, which predestine it for use in agriculture and environmental protection in the broadest sense. Organic carbon is the basic element responsible for maintaining soil fertility. Depletion of soil organic matter in agricultural areas has been observed for several decades. The addition of biochar to soil is one of the new solutions to improve soil fertility. Currently, there is an increase in the concentration of carbon dioxide in the atmospheric air worldwide, causing an increase in air temperature, together with other greenhouse gases. The effect of these changes is to negatively alter soil fertility, its chemical, physical and biological properties [Pak et al., 2016]. One solution to mitigate the occurrence of adverse environmental changes is to increase the intensity of soil carbon sequestration with biochar. The introduction of biochar into the soil increases soil fertility, crop yields [Lehmann and Joseph, 2012], and the productivity and profitability of agricultural production [Atkinson et al., 2010]. Biochar is defined as a high-carbon product obtained from various organic materials including manure, straw, wood, leaves by pyrolysis, with high stability and longevity in the soil [Shackley et al., 2012]. The solid fraction obtained by pyrolysis is called biochar. The other two fractions are the gas fraction, which is a mixture of gaseous hydrocarbons, and the liquid fraction, referred to as oil, which is a mixture of liquid hydrocarbons. There are six main types of pyrolysis technology: fast pyrolysis, flash pyrolysis, slow pyrolysis, vacuum pyrolysis, hydro pyrolysis and microwave pyrolysis [Li et al., 2022]. The pyrolysis process takes place under strict conditions and limited or no oxygen [Sohi, 2012]. This process makes it possible to manage various types of plant material residues and biomass in an environmentally friendly manner. Unlike composting or open burning, where air-polluting compounds, i.e. H_2S, SO_2, and NH_3, are emitted [Alhazmi and Loy, 2021; Chungcharoen and Srisang, 2020], pyrolysis is a new technology for biomass reuse in line with global net zero emission targets. Biochar, as a carbon-rich material, is used in a wide variety of applications due to important characteristics such as specific surface area, pore volume, calorific value, functional groups on the surface, cation exchange capacity and structural properties [Wang and Wang, 2019]. Due to its specific properties, it can be an absorbent for the removal of water and air pollutants. There is also potential for the catalytic use of biochar in various industrial processes including biodiesel production, gas production and as microbial fuel cell electrodes [Lee et al., 2017]. The performance of biochar in these applications and the associated environmental impact depends on the physicochemical properties of the biochar, which are closely related to the pyrolysis process conditions and feedstock composition [Li et al., 2019; Sun et al., 2017]. This paper discusses a number of properties of different biochar produced from different biomass sources, characterises their properties and presents the possibilities of their management both in the context of their suitability for agricultural and environmental purposes.

Conditions for the formation of biochar by pyrolysis

Biochar is produced by the transformation and decomposition of organic matter subjected to temperatures in the range 200-900 °C [Sohi, 2012]. The proportions of the various products of biomass pyrolysis depend on the pyrolysis process parameters such as; temperature ramp rate, decomposition time i.e. residence time at final temperature, process temperature and pressure (Table 1).

Slow pyrolysis (biocarbonisation) takes place under conditions of slow temperature rise (less than 10 °C·s^{-1}) and long exposure time – several hours. The main product of the process is biochar. Typically, the temperature rise time is between 0.1 and 1 °C·s^{-1} and the residence time is long 300–7200 seconds, with pyrolysis temperatures in the range of 300–700 °C [Li and You, 2022]. The low rate of temperature elevation limits the formation of secondary products and thermal cracking of biomass components, favouring the formation of biochar as the main product with a high proportion of amorphous carbon [Chen et al., 2003; S and P, 2019]. Pyrolysis of maize cobs, rice straw and hulls and wheat straw at a low temperature of 300–450 °C and a residence time of 3600 s and a temperature increase of 0.33 °C·s^{-1} provides a biochar yield of a maximum of 43% a higher temperature to 450 °C reduces the biochar formation efficiency to 35% [Biswas et al., 2017]. Slow pyrolysis yields the highest proportion of the solid fraction of about 35%. This process is also carried out at 500 °C, but the residence time of the substrate at this temperature is significantly longer, ranging from 5 to 30 minutes. With regard to gasification, where the temperature is maintained above 800 °C and the residence time at the final temperature of the substrate is 10–20 seconds, only 10% of the solid fraction is produced. Under these conditions, the predominant product is the gas fraction, which accounts for 85% [Malińska et al., 2014]. The fast pyrolysis process takes place under conditions of rapid temperature rise (> 103 °C·s^{-1}) and short reaction time (< 2 s) with rapid cooling of volatiles leading to the formation of biooil and biochar as an intermediate [Zhao et al., 2020]. In addition, catalysts and microwave assistance are often used in the thermal conversion of biomass to improve product distribution and quality [Lu et al., 2021; Zulkornain et al., 2022]. Most often, high-speed pyrolysis takes place under conditions where the temperature builds up by 10–200 °C·s^{-1}, favouring oil formation and reducing carbon formation [Liu et al., 2020]. Under conditions where the pyrolysis temperature is 500–1200 °C·s^{-1} and the

Table 1. Proportion of pyrolysis products carried out under different process conditions [Lewandowski et al., 2011]

Pirolitic process	Pyrolysis process share of fractions obtained in different pyrolysis processes in %		
	Liquid fraction	Gas fraction	Liquid fraction
Fast pyrolysis	75	Fast pyrolysis	75
Moderate pyrolysis	50	Moderate pyrolysis	50
Biocarbonisation	30	Biocarbonisation	30
Gasification	5	Gasification	5

time of temperature ramp-up phases is controlled to be 0.5–10 s, thermal cracking of the biomass occurs, limiting carbon formation [Ghysels et al., 2019; Tripathi et al., 2016]. Typically, under these conditions, about 12% biochar is formed relative to the weight of the products obtained while the liquid fraction products predominate.

The properties of the solid fraction that determine its practical applications

The solid fraction extracted by pyrolysis called biochar has a number of properties that determine its high potential for practical applications. These include biochar characteristics such as chemical composition, stability, specific surface area, and porosity [Malińska et al., 2014].

The chemical composition of biochar varies considerably, which depends critically on the type of substrate from which it is made and also on the conditions under which the pyrolysis process is carried out [Gaskin et al., 2008]. Biochar is characterised by an alkaline reaction reaching a pH even above 10.0 on the pH scale [Naeem et al., 2014]. The main component of biochar is stable organic carbon and, in smaller quantities, so-called leachable carbon [Naeem et al., 2014; Thabelo, 2018; Trompowsky et al., 2005]. In addition, an important component of biochar is ash, which contains minerals, macro- and micronutrients important for fertiliser potential. During the formation of biochar, the carbon content increases relative to the raw material from which the biochar is formed [Gaskin et al., 2008]. During formation, the amount of nitrogen in biochar decreases regardless of temperature, but the total nitrogen content decreases with increasing temperature [Bera et al., 2014]. As temperature increases, an increase in the macro and micronutrient content of various biochar materials is observed [Mimmo et al., 2014]. Examples of macro and micronutrient contents are shown in Table 2. The amount of nutrients is influenced by the biochar fraction. The finest fractions < 1–2 mm contain significantly more nutrients than the coarser fractions [Angst and Sohi, 2013; Prasad et al., 2020]. Biochar differs from other types of organic matter in that it contains significantly more aromatic carbon compounds, which, due to the large number of functional groups, determine its sorption properties towards ions [Krull et al., 2012]. This characteristic makes biochar similar to soil humus and thus can be used as a means of improving the properties of light soils. In addition, biochars, unlike soil humus, show little susceptibility to microbial decomposition [Cheng et al., 2008], and therefore exhibit considerable stability once introduced into the soil.

The physical properties of biochar, shaped by the pyrolysis process, largely determine its multidirectional use, especially in agriculture and environmental protection. Biochar is characterised by an exceptionally developed internal porous structure and an associated large specific surface area, which, depending on the temperature of the pyrolysis process, is in the range

Table 2. Chemical composition of different types of biochar expressed as content of total elemental forms

Biochar	Parameter											Source
	pH	C g·kg^{-1}	N g·kg^{-1}	P g·kg^{-1}	K g·kg^{-1}	Ca g·kg^{-1}	Mg g·kg^{-1}	Zn ppm	Fe ppm	Mn ppm	Temp. °C	
Pine wood	9.2	549	0.7	4.89*	1.32	-	-	-	-	-	>500	[Thabelo, 2018]
Wheat straw	7.7	517	13.8	2.6	30	6.3	4.5	47	158	106	300	[Naeem et al., 2014]
Wheat straw	8.8	620	9.4	3.0	32	8.3	5.6	59	259	117	400	[Naeem et al., 2014]
Wheat straw	9.4	662	8.5	3.4	36	8.7	6.9	70	422	163	500	[Naeem et al., 2014]
Rice straw	8.0	452	11.5	1.1	36	9.1	8.1	67	195	396	300	[Naeem et al., 2014]
Rice straw	9.7	555	9.8	1.3	41	9.8	9.6	89	341	554	400	[Naeem et al., 2014]
Rice straw	10.4	630	8.5	1.4	48	13.3	11.3	98	521	649	500	[Naeem et al., 2014]
Chicken manure	10.1	392	34.7	30.1	51.1	42.7	10.7	628	6060	596	400	[Gaskin et al., 2008]
Chicken manure	9.7	392	30.9	35.9	58.6	50.4	12.9	752	8030	725	500	[Gaskin et al., 2008]
Ground nut shells	10.5	732	24.3	1.83	15.2	4.62	2.19	35	1000	116	400	[Gaskin et al., 2008]
Ground nut shells	10.1	804	24.8	1.97	16.4	5.12	2.50	37	1150	131	500	[Gaskin et al., 2008]

Note: * – amount of phosphorus in bioavailable form, expressed in mg P·kg^{-1}.

of 80 - 200, sometimes above 400 $m^2 \cdot g^{-1}$ [Chun et al., 2004]. Among all pores, different pore sizes are distinguished, respectively macropores > 50nm, mesopores 2-50 nm, micropores <2 nm, nanopores <0.9 nm [Ahmedna et al., 2004; Downie et al., 2012]. A change in the structure of organic matter occurs during pyrolysis, accompanied by the formation of pores, increasing the proportion of micropores with increasing pyrolysis temperature [Katyal et al., 2003]. At temperatures above 800 °C, the specific surface area of the material decreases due to partial melting of the carbonaceous material [Lua et al., 2004]. These features also determine the extremely high sorption properties of biochar towards cations, which, depending on the pyrolysis temperature, reach values in the range of 100 – 300 $mmol \cdot kg^{-1}$, the higher the pyrolysis temperature the lower the exchange sorption capacity [Méndez et al., 2013; Song and Guo, 2012]. An increase in the pyrolysis temperature from 250 to 600 °C results in a decrease in the sorption capacity of biochar towards heavy metals by more than 3 times [Ding et al., 2014]. The above-mentioned physical characteristics of biochar determine their ability to retain water and their sorption properties that determine their ability to retain plant nutrient elements. The water retention of biochar is due to the proportion of micro pores < 10 μm in diameter and the material from which it is formed. Materials with a higher lignin content have a negative correlation of water retention capacity [Wang and Xing, 2007]. Biochar materials with a higher content of aromatic groups relative to aliphatic groups have a higher water absorption capacity [Zhao et al., 2018]. Biochar materials with a higher content of aromatic groups relative to aliphatic groups have a higher water absorption capacity [Sun et al., 2014]. The specific surface area of biochar from maize straw at a formation temperature of 700 °C has a very high specific surface area of up to 251 $m^2 \cdot g^{-1}$ [Zhao et al., 2018]. The chemical and physical properties of biochar, such as, in particular, the high content of organic carbon in stable form and minerals, and the strongly developed internal porosity and specific surface area, mean that it can find wide application in various areas of agriculture and environmental protection

Possibilities for economic use of the solid fraction obtained in the pyrolysis process

The biochar obtained from pyrolysis can be directly used in many areas of the economy. A wide range of possibilities in this regard is outlined below. It should also be emphasised that biochar obtained from pyrolysis is also a raw material for further processing into so-called activated carbon, which is increasingly used in the broader field of environmental protection.

Use of biochar in bioenergy as a solid fuel. The energetic use of biochar is the oldest and best-known direction of its economic use. By definition, it is a carbon-rich "a carbon (C)-rich product’" [Lehmann and Joseph, 2012]. It can be burned or co-fired in power plants providing an alternative to fossil fuels. The pyrolysis process provides an increase in the energy value of the resulting product, due to the volatilisation of other elements, i.e. S, O, H, N, and the concentration of carbon in the final product. The pyrolysis process can increase the energy value of plant materials, i.e. nut shells, by 30–40% [Suman and Gautam, 2017]. The calorific value (Table 3), as can be seen from the data in the table below, is similar to that of hard coal and higher than that of lignite and higher than that of biomass.

Table 3. Parameters of selected fuels and biochar obtained from different types of substrates [Malińska et al., 2014]

Selected fuels	Calorific value MJ·kg-1	Coal % C	Volatile matter %	Ash %
Fossil fuels				
Natural gas	48.0	75.0	100.0	0.0
Hard coal	25.0	60.0	25.0	12.0
Lignite	7.5–21.0	66.0–73.0	40.0–60.0	20.0–20.0
Biomass				
Wood	10.5	35.0	55.0	1.0
Straw	15.0	43.0	73.0	3.0
Biochar				
Rapeseed straw biochar	23.4	72.7	13.6	21.8
Cherry wood biochar	27.7	59.5	22.2	9.1

Use in fertilisation to improve soil properties. Biochar is a material that is produced under natural conditions around the world as a result of forest fires, so its long-term positive effects on the soil environment and the recovering forest vegetation after a fire are largely understood. A number of studies have shown that the addition of biochar to poor and degraded soils as a result of their excessive agricultural use contributes significantly to improving their fertility and productivity (Table 4) [Beesley et al., 2011; Nigussie, 2012]. In addition, a reduction in nitrous oxide (N_20) and methane (CH_4) emissions has been observed under the influence of soil fertilisation with biochar [F. Verheijen, 2010]. The application of biochar affects a number of chemical physical and biological properties. Soil pH is increased as a result of (I) the introduction of alkaline material and (II) the potential reduction in toxicity of active aluminium [Butnan et al., 2015; Syuhada et al., 2016].

The effectiveness of biochar substrates is as follows: manure > wood > lignin-cellulosic materials > green plant parts. The effectiveness of increasing soil pH is generally not correlated with the temperature of biochar formation [Singh et al., 2022]. The incorporation of biochar into the soil increases the sorption capacity of the soil. The most effective changes occur on light soils where this increase can be around 33–37%. The sorption capacity of soils is influenced by the temperature of biochar formation, with biochar formed at high temperatures being more effective. The type of material used to make biochar is not significant in terms of changes in soil sorption capacity [Singh et al., 2022]. The use of biochar affects the organic matter content of the soil. The carbon content is influenced by the biochar application rate; at high application rates (> 80 $t \cdot ha^{-1}$) the average increase in organic carbon content is over 40%, at medium application rates (40–80 $t \cdot ha^{-1}$) the increase is 37%, at low application rates (< 40 $t \cdot ha^{-1}$) the increase is 20%. The type of biochar used is not significant from the point of view of the efficiency of increasing soil organic carbon content in contrast to the temperature of formation, achieving higher efficiencies for lower pyrolysis temperatures < 500 °C than for high pyrolysis temperatures > 500 °C. Soil porosity also increases under the influence of biochar, with an increase in total porosity of up to 78% when average doses are applied under field conditions [Singh et al., 2022]. The application of biochar also affects soil microbial biodiversity. The type of biochar used, with the advantage of biochar made from green plant residues, has a strong effect on shaping biodiversity compared to other types, i.e. wood, lignin-cellulosic waste. In contrast, the increase in soil fungal diversity was most effective after the application of biochar from lignin-cellulosic waste, to a lesser extent from green plant residues, and no change after the application of wood biochar [Singh et al., 2022]. The use of biochar for fertilisation also significantly increases the content of bioavailable forms of soil nutrients such as phosphorus, potassium, calcium and magnesium [Novak and Busscher, 2013]. The effect of biochar fertilisation on soil properties and nutrient abundance is illustrated by the results in the table below. The data also indicate a significant increase in soil organic carbon content under biochar fertilisation. This carbon with organic carbon status increases the organic carbon stock in the soil, a stock that is much more permanent than natural humus.

Disadvantages of biochar. Biochar as a fertilizer material, in addition to its undoubted advantages, also has disadvantages that must be taken into account when using it in agriculture. One of them is the varying chemical composition [Cantrell et al., 2012; Gul et al., 2015; Singh et al., 2010]. Depending on the biomass used and the conditions of the pyrolysis process, biochar can have low or high carbon content above 50%, varying C: N ratios, or variable mineral content. Biochar can also contain varying amounts of aromatic compounds [Jindo et al., 2014; Leng and Huang, 2018; Wang et al., 2015] and aliphatic [Liu et al., 2015] and easily degraded oxidized

Table 4. Effect of biochar application on selected properties of sandy soil [Novak and Busscher, 2013]

Type of biochar	Pyrolysis rate	pH	CEC[1]	$C_{org.}$	$N_{0g.}$	P	K	Ca	Mg
			$mol(+) \cdot kg^{-1}$	$g \cdot kg^{-1}$		$mg \cdot kg^{-1}$ (bioavailable forms)			
Control	-	5.2	1.8	2.81	0.22	29.0	14.0	100.0	14.0
Peanut shells	500 °C	7.4	2.1	19.5	0.71	33.0	145.0	179.0	37.0
Hardwoods	fast	6.2	2.3	17.2	0.37	22.0	46.0	157.0	18.0

Note: [1] CEC – cation exchange capacity.

carbon compounds [Buss and Mašek, 2016]. In addition, the fertilizer components contained in biochar are slowly released into plant-available forms, with higher temperatures and longer residence times, promoting the accumulation of total P and K [Peng et al., 2011; Xie et al., 2015] and the release of Ca, Mg and Si and the retention of Fe, Mn i S [Qambrani et al., 2017]. Studies have also shown that some biochar can contain toxic compounds and contaminants t.j. dioxins (PCDD/Fs) and polycyclic aromatic hydrocarbons (PAHs) [Lyu et al., 2016; Zielińska and Oleszczuk, 2016], whose formation is recorded during thermal conversion of biomass. Toxic substances can be released into the soil/air/water environment when using biochar, which can pose secondary pollution and ecological risks. In addition, in remediation applications, biochar can also be a carrier of heavy metals [Xu et al., 2019]. These unfavorable characteristics of biochar create problems with its standardization and result in the fact that its legal status as a material used in agricultural production is so far not legally regulated in the European Union [Commision, 2016]. The process of legalizing biochar "as a product for plant nutrition" has been in the draft phase of the harmonization of the Community Fertilizer Law for several years. So far, only some biochar organizations have developed their own quality standards for biochar and the resulting certification of biochar. These are in the US the International Biochar Initiative (IBI) and in Europe the European Biochar Foundation and the British Biochar Foundation (These are respectively; IBI Biochar Standards, European Biochar Certificate and Biochar Quality Mandate). Participation in these quality systems is voluntary.

The use of biochar can generate higher CO_2 greenhouse gas emissions under certain conditions [Yang et al., 2017], N_2O [Lee et al., 2022; Liu et al., 2014], CH_4 [Ribas et al., 2019]. Fertilizer use of biochar itself is burdened with other drawbacks, the main ones being its low density and hydrophobic properties. Dust, especially PM_{10}, is the most serious health risk associated with biochar, as well as the most difficult aspect of its use in the field [Li et al., 2018; Ravi et al., 2016]. Small carbon particles can irritate and cause lung damage if inhaled [Sahu et al., 2014; Schenker et al., 2009]. Due to these characteristics, the use of biochar as an additive to natural and organic fertilizers and composts is recommended in agricultural practice. The lack of widespread use of biochar is due to the ambiguity of the methodology of introducing biochar into the soil, especially in small-scale or no-till farming. There is a lack of comprehensive studies on the behavior of different forms of carbon compounds and their stability, studies related to the risk of introducing heavy metals into the soil and even the possibility of reducing the effectiveness of chemicals used in plant protection [Cheng et al., 2017]. Field studies are particularly important in this regard, as most of the experiments on the properties of biochar have been done at the laboratory and short-term field level.

Biochar as an additive to natural fertilisers and organic manures. Natural fertilisers such as the commonly used manure or slurry are characterised by considerable odour, which becomes particularly apparent when these fertilisers are applied to agricultural fields. This is particularly troublesome if these natural fertilisers are applied to fields close to human settlements. The addition of a few to several weight percent of biochar to these fertilisers eliminates the odour of these fertilisers to a great extent or reduces or even eliminates them completely. This is due to the sorption properties of biochar towards all kinds of chemical compounds, including those in gaseous form. After being applied to fields, natural fertilisers undergo rapid decomposition processes, resulting in the release of gaseous ammonia. Fertiliser nitrogen losses from natural fertilisers can be considerable, which significantly reduces their fertiliser value. The addition of biochar during storage of these fertilisers significantly eliminates these losses. A similar odour- and ammonia-reducing effect is obtained from the addition of biochar to various organic materials processed into organic fertilisers. This includes materials such as sewage sludge, waste ash substrate.

Biochar as an additive to composts. The composting of any organic material involves providing optimal conditions in the compost heap for the aerobic decomposition of organic compounds. Therefore, the composting materials must also include structuring materials to prevent excessive compaction of the compost mass which would hinder the access of air. During these processes, organic compounds decompose, carbon dioxide, the main product of this aerobic process, escapes, the C: N ratio narrows and from the decomposed organic matter the mineral forms of the fertiliser components available to plants are released and the compost acquires the status of fertiliser material. During the composting process, which sometimes lasts several months, odorous gaseous products are also released. In addition, the ammonium nitrogen produced by the mineralisation of the organic matter may undergo nitrification to form nitrates, which in turn promotes the leaching of this form of nitrogen from the compost heap. The addition of a few percent of biochar eliminates all these above-mentioned negative effects of the transformations occurring during composting. Biochar binds the gaseous products formed in the process, including ammonia, reduces odour, binds the ammonium form limiting nitrification and thus protects mineral nitrogen from leaching from the compost heap. In addition, biochar added to the compost acts as a structuring material and also provides fertilising components. All the above-mentioned characteristics of biochar allow it to be recommended as a very good component of composting materials [Dias et al., 2010; Malińska et al., 2014].

Biochar as an ingredient in animal bedding. Livestock can be kept in livestock buildings on bedding or in what is known as a slurry system. Litter has absorbent properties and, when mixed with animal faeces and urine, improves hygienic conditions in the building. In the alcove system, which is the most commonly used, the mixture of faeces and litter that constitutes the natural fertiliser – the manure – is removed each day to the slurry pit, from where the manure is taken to the fields twice a year in spring and autumn. In the housing and in the slurry house, microbiological transformations take place in the manure, resulting in various odorous volatile substances and ammonia as a product of protein decomposition. These are highly undesirable phenomena during storage which, in addition to their negative impact on animal health, contribute to significant nitrogen losses, thus reducing the fertilising value of the manure. Nitrogen losses in the form of ammonia emissions are particularly high from litter on poultry farms. These losses occur both in the housing and in the piles during storage and handling of chicken manure. This extreme susceptibility of poultry manure to nitrogen losses in the form of ammonia is due to the specificity of poultry manure compared to pig or cattle manure [Gerlach H., 2014]. These excreta, due to the fact that poultry do not excrete urine, contain easily decomposed simple organic compounds (such as urea, uric acid, hippuric acid), which easily decompose into mineral forms and alkalise the environment. As a result, poultry droppings have an alkaline reaction which causes the mineral nitrogen formed by the decomposition of organic compounds in the form of ammonium ion to volatilise as ammonia under these conditions. These losses on poultry farms can be significant, given that the nitrogen content of chicken faeces is three to four times higher than that of cattle or pig faeces. Biochar, due to its gas sorption properties, can be an excellent preparation component that, when added to bedding in a livestock building, or mixed with manure during storage in a pile, or added to slurry, will essentially bind the resulting gaseous products including ammonia and volatile odorous substances [Steiner et al., 2010].

Biochar as an additive to silage. Biochar can also be used as an additive for silage. As shown in a study conducted in Germany, the addition of biochar to silage increased the healthiness of this feed in cattle feeding. When silage was fed with biochar supplementation, there was a reduction in the incidence of diarrhoea and the number of fertility disorders in the herd decreased. Most generally, biochar supplementation resulted in a beneficial ‘tonic’ effect in cattle nutrition [Gerlach H., 2014].

Biochar as a means of sequestering carbon in the soil. The increase in atmospheric CO2 emissions that is currently taking place is leading in the long term to a growing imbalance in carbon emissions and absorption in nature. Ways are therefore being sought to capture and store it in a stable form outside the atmosphere. One way is to store it in the soil in the form of biochar. When introduced into the soil, biochar allows for long-term carbon storage. The addition of 13.5 $t \cdot ha^{-1}$ of biochar to soil, representing 0.3 % of the top 30 cm of soil, is estimated to provide carbon storage for at least two centuries. It is estimated that if 10% of the world’s biomass resources were converted to biochar with a process efficiency of 50% and obtaining 30% of the energy from volatile matter, carbon sequestration of about 20% of the current annual increase in atmospheric carbon would be possible [Matovic, 2011].

Biochar as a remediation agent for contaminated soils. Contamination of soils with various organic substances (e.g. aromatic hydrocarbons from oil pollution) or inorganic substances (heavy metals) is increasingly common in various regions of the world, posing threats to living organisms and humans. Therefore, solutions are being sought to cheaply and effectively remove harmful substances from contaminated ecosystems and revitalise them. Such an effective solution could be the addition of biochar to contaminated soils. Thanks to its properties, it can permanently sorb various chemical compounds and lead to their immobilisation in the soil environment and essentially reduce their bioavailability [Beesley et al., 2011].

Other applications of biochar. A number of studies have demonstrated many interesting uses for biochar. Due to its sorption properties, biochar has been shown to absorb ethylene, a gas excreted by fruit and vegetables - accelerating their ripening. This characteristic of biochar has found its way into the food industry to produce packaging with biochar added, thus extending the expiry date of products. Another use of biochar is the production of biodegradable pots from it for horticultural production applications, seed strips and germinator strips for mechanised systems in horticulture. Other applications of biochar include the possibility of its use in the production of surgical and sweat garments and biodegradable bags for organic waste [HP, 2012]. Biochar has also found use in electronics as a semiconductor and component of lithium-sulphur batteries. It can be used to produce porous carbon-sulphur nano-elements as a cathode in these batteries [Gu et al., 2015].

Biochar obtained by pyrolysis as raw material for the production of carbon adsorbents

Carbon adsorbents, known as activated carbons, are products obtained by pyrolysis of various organic materials and further activated by physical or chemical methods. Thus, pyrolysis is the first step in the production of activated carbons. In this process, under anaerobic conditions, the organic material is destroyed and a porous structure is produced. However, this structure is disordered and the free internal spaces can be filled with tar compounds from the decomposition of the input material, which significantly reduces the specific surface area of the produced biochar. Only the second step of subjecting biochar to activation processes allows to expand its porous structure and increase its specific surface area many times over, which creates new possibilities for its practical applications as absorbents in different areas of the economy [Hays et al., 1976; Walker Philip L.Jr. and L. Figueiredo, 1986].

Activation processes for biochar can be carried out by physical and chemical methods. Physical activation involves treating the solid pyrolysis product with oxidising gases at high temperature. Chemical activation uses, in the treatment of the raw material after pyrolysis, concentrated aqueous solutions of various compounds such as; acids (e.g. H_3P0_4) alkalis (e.g. KOH) or salts (e.g. $ZnCl_2$, K_2S). As a result of the activation process, a significant part of the mass of the carbonised material is lost. Depending on the type of raw material and the desired sorption properties, the mass of the final product obtained is between 10 and 40% of the initial mass. The porous structure of activated carbons is made up of pores of different sizes, which, according to the current classification, are divided into three groups; micropores (< 2 nm), mesopores (2–50 nm) and macropores (>50 nm). The pores that determine to the greatest extent the specific surface area and thus the sorption properties of activated carbons are the micropores [Sing et al., 1985]. Activated carbons are products with a wide range of applications in many industries (Table 5).

The main exemplary application directions are as follows:

(I) Gas cleaning: odour removal, flue gas cleaning of toxic substances, VOC capture and solvent recovery, separation of gas mixtures, reduction of exhaust emissions from fuel combustion in transport. (II) Water and waste water treatment: drinking water treatment, swimming pool water treatment, industrial process water treatment, groundwater treatment, industrial waste water treatment, landfill leachate treatment. (III) Purification of substances: purification of substrates and products in the food industry, purification of liquids in the chemical and pharmaceutical industries, cosmetic industry, gold recovery. (IV) Other applications: catalyst carriers, respiratory protection, energy storage.

Active coals by physical form can be divided into three groups: (i) dusty activated carbons - PAC (Powder Activated Carbon), (ii) granular activated carbons – GAC(Granular Activated Carbon), (iii) extruded activated carbons – EAC (Extruded Activated Carbon) [S. Rangabhashiyam, 2019].

Examples of the use of activated carbons are given below [Dębowski Z., 2004; Henning KH, 1991; Izquierdo et al., 2003; S., 2019; Tsuji and Shiraishi, 1997]:

- DAC dusty activated carbons, have grain diameters of less than 0.2 mm after grinding. They are most commonly used for; (I) the

Table 5. Typical values for basic structural parameters of activated carbons [S. Rangabhashiyam, 2019]

Raw material	Total pore volume ($cm^3 \cdot g^{-1}$)	Average pore radius (nm)	Specific surface area ($m^2 \cdot g^{-1}$)
Activated carbons used in gas purification			
Coconut shells	0.5–0.6	1.0–1.1	1000–1100
Peat	0.6–0.7	1.1–1.2	1000–1250
Brown coal	0.9–1.0	2.9–3.2	600–675
Black coal	0.6–0.7	1.2–1.4	1000–1150
Activated carbons used in liquids treatment			
Wood (chemical activation)	1.4–1.8	2.2–2.6	1200–1600
Peat	1.1–1.2	2.3–2.6	900–1050
Brown coal	0.9–1.0	2.9–3.2	600–675

treatment of drinking water (surface water during algal blooms or for the reduction of humus compounds); (II) the reduction of COD (chemical oxygen demand) and AOX (adsorbable organically bound halogens) in wastewater treatment; (III) enrichment of activated sludge in wastewater treatment plants; (IV) decolourisation of chemical and food products; (VI) removal of dioxins, furans, mercury and other pollutants from fuel combustion gases; (VII) as a carrier of bacterial colonies in biological wastewater treatment processes.

- GAC granular activated carbons are adsorbents with an irregular shape and a grain size of grains of 0.2 to 5.0 mm. They are most commonly used for: (I) purification of drinking water in municipal water treatment plants (improvement of colour, taste, odour, removal of pesticides and humus compounds); (II) catalytic removal of residual chlorine and ozone in water treatment; (III) removal of various organic compounds in wastewater treatment; (IV) removal of hydrocarbons in water and land remediation; (V) decolourisation of food products (sugar, glucose); (VI) purification of paraffin and pharmaceutical glycerine.
- EAC moulded activated carbons, are in the form of cylinders with diameters ranging from 0.8 to 5.0 mm. They are most commonly used for; (I) – purification of drinking water in municipal water treatment plants (improvement of colour, taste, odour, removal of pesticides and humus compounds); (II) reduction of volatile organic compounds (VOCs); (III) purification of reaction gases from various types of pollutants; (IV) respiratory protection; (V) deodorisation of air e.g. waste handling halls, wastewater treatment plant rooms, biogas plant rooms, air discharged from composting plants; (VI) recovery of organic solvents; (VII) purification of natural gas and biogas. Growing public awareness of the need to protect the environment has resulted in a steadily increasing global demand for activated carbons (Table 6).

Between 2007 and 2016, the global market for activated carbons doubled to an estimated 1,770,000 Mg. Market forecasts estimate that global demand will grow at an annual rate of 5.3% (w/w). The main reasons for this growth will be increasing requirements in the form of new directives and regulations for water treatment quality, wastewater treatment and reduction of toxic emissions (e.g. mercury) from energy processes. On this basis, it can be predicted that the total global demand for activated carbons in 2025 could

Table 6. World demand and production capacity for activated carbons from 2007 to 2021 in thousand Mg [Roskill, 2017]

World region	Annual demand			Annual capacity		
	2007	2016	2021	2007	2016	2021
Europe	100	225	Europe	100	225	Europe
USA	210	463	USA	210	463	USA
China	45	514	China	45	514	China
Japan	120	190	Japan	120	190	Japan
India	40	108	India	40	108	India
Others	135	270	others	135	270	others
World	650	1770	World	650	1770	World

reach a value of approximately 2707,000 Mg. Global production of activated carbons is increasing steadily, as shown in the table above. Analysis of the data (Table 6) in the above table shows that Europe and Japan are areas where demand for activated carbons exceeds their production potential, indicating that their needs are met by imports, mainly from China.

Poland's production potential for activated carbons is approximately 2.8 thousand Mg·year^{-1} and is insufficient. The volume of imports of activated coals to Poland amounted in 2015 to. 5.1 thousand Mg. The largest share of imports comes from Germany (1.8 thousand Mg), China (0.6 thousand Mg), USA (0.4 thousand Mg), Belgium (0.4 thousand Mg). Carbon adsorbent prices on world markets depend on their activated carbon type and are; PAC – 1–4 \$·kg^{-1}; GAC – 2.5–4 \$·kg^{-1}; EAC – 2.5–6 \$·kg^{-1} [Roskill, 2017].

CONCLUSION

Biochar meets all the criteria of a good fertiliser material supplying plants with nutrients and improving the physical properties of soil, increasing its water holding capacity, sorption properties and reducing acidification. Its characteristics and properties predestined it particularly as a fertiliser material for light soils, such as those prevailing on the majority of agricultural land in Poland. Biochar as a material for agricultural production is still the subject of scientific research aimed at developing universal quality standards to ensure the full safety of its use. The effects of biochar on plant growth and bioavailability of heavy metals and pollutants require special attention. The pyrolysis of waste biomass is an increasingly important element of activities in the area of a closed loop economy. It makes it possible to convert many waste materials into new products with economically important functional characteristics. This applies to both solid pyrolysis products - biochar - and the liquid fraction - oil. Biochar obtained from biomass pyrolysis has a wide range of applications, which are presented in this study. They are also a valuable raw material for the production of carbon adsorbents, which are playing an increasingly important role in broader environmental protection. As attempted to demonstrate, there is a growing demand in the global economy for activated carbons derived from pyrolytic biochar.

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REFERENCES

1. Ahmedna, M., Marshall, W.E., Husseiny, A.A., Rao, R.M., Goktepe, I. 2004. The use of nutshell carbons in drinking water filters for removal of trace metals. Water Research, 38(4), 1062–1068.
2. Alhazmi, H., Loy, A.C.M. 2021. A review on environmental assessment of conversion of agriculture waste to bio-energy via different thermochemical routes: Current and future trends. Bioresource Technology Reports, 14.
3. Angst, T.E., Sohi, S.P. 2013. Establishing release dynamics for plant nutrients from biochar. GCB Bioenergy, 5(2), 221–226.
4. 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 and Soil, 337(1), 1–18.
5. Beesley, L., Moreno-Jiménez, E., Gomez-Eyles, J.L., Harris, E., Robinson, B., Sizmur, T. 2011. A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. Environmental Pollution, 159(12), 3269–3282.
6. Bera, T., Purakayastha, T.J., Patra, A.K. 2014. Spectral, chemical and physical characterisation of mustard stalk biochar as affected by temperature. Clay Research, 33(1), 36–45.
7. Biswas, B., Pandey, N., Bisht, Y., Singh, R., Kumar, J., Bhaskar, T. 2017. Pyrolysis of agricultural biomass residues: Comparative study of corn cob, wheat straw, rice straw and rice husk. Bioresource Technology, 237, 57–63.
8. Buss, W., Mašek, O. 2016. High-VOC biochar—effectiveness of post-treatment measures and potential health risks related to handling and storage. Environmental Science and Pollution Research, 23(19), 19580–19589.
9. Butnan, S., Deenik, J.L., Toomsan, B., Antal, M.J., Vityakon, P. 2015. Biochar characteristics and application rates affecting corn growth and properties of soils contrasting in texture and mineralogy. Geoderma, 237, 105–116.
10. Cantrell, K.B., Hunt, P.G., Uchimiya, M., Novak, J.M., Ro, K.S. 2012. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. Bioresource Technology, 107, 419–428.

11. Chen, G., Andries, J., Luo, Z., Spliethoff, H. 2003. Biomass pyrolysis/gasification for product gas production: The overall investigation of parametric effects. Energy Conversion and Management, 44(11), 1875–1884.
12. Cheng, C.H., Lehmann, J., Engelhard, M.H. 2008. Natural oxidation of black carbon in soils: Changes in molecular form and surface charge along a climosequence. Geochimica et Cosmochimica Acta, 72(6), 1598–1610.
13. Cheng, H., Jones, D.L., Hill, P., Bastami, M.S. 2017. Biochar concomitantly increases simazine sorption in sandy loam soil and lowers its dissipation. Archives of Agronomy and Soil Science, 63(8), 1082–1092.
14. Chun, Y., Sheng, G., Chiou, G.T., Xing, B. 2004. Compositions and sorptive properties of crop residue-derived chars. Environmental Science and Technology, 38(17), 4649–4655.
15. Chungcharoen, T., Srisang, N. 2020. Preparation and characterization of fuel briquettes made from dual agricultural waste: Cashew nut shells and areca nuts. Journal of Cleaner Production, 256.
16. Commision, E., 2016. Regulation of the European Parliament and of the Coincil laying down rules on the making available on the market of CE marked fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009.
17. Dias, B.O., Silva, C.A., Higashikawa, F.S., Roig, A., Sánchez-Monedero, M.A. 2010. Use of biochar as bulking agent for the composting of poultry manure: Effect on organic matter degradation and humification. Bioresource Technology, 101(4), 1239–1246.
18. Ding, W., Dong, X., Ime, I.M., Gao, B., Ma, L.Q. 2014. Pyrolytic temperatures impact lead sorption mechanisms by bagasse biochars. Chemosphere, 105, 68–74.
19. Downie, A., Crosky, A., Munroe, P. 2012. Physical properties of biochar, Biochar for Environmental Management: Science and Technology, 13–32.
20. Dębowski Z., L.J. 2004. Krajowe stacje uzdatniania wód powierzchniowych stosujące węgle aktywne. Materiały konferencyjne „Węgiel Aktywny w Ochronie Środowiska i Przemyśle", Wyd. Pol. Częstochowskiej. (in polish)
21. Verheijen F., Jeffery S., Bastos A., Van Der Velde M., Diafas I.F. 2010. Biochar Application to Soils A Critical Scientific Review of Effects on Soil Properties, Processes and Functions, Office for the Official Publications of the European Communities, Luxembourg, 149.
22. Gaskin, J.W., Steiner, C., Harris, K., Das, K.C., Bibens, B. 2008. Effect of low-temperature pyrolysis conditions on biochar for agricultural use. Transactions of the ASABE, 51(6), 2061–2069.
23. Gerlach H., S.H.P. 2014. Biochar in poultry farming. The Biochar Journa. Arbaz, Switzerland. ISSN 2297-1114. The Biochar Journal, Arbaz, Switzerland.
24. Ghysels, S., Estrada Léon, A.E., Pala, M., Schoder, K.A., Van Acker, J., Ronsse, F. 2019. Fast pyrolysis of mannan-rich ivory nut (Phytelephas aequatorialis) to valuable biorefinery products. Chemical Engineering Journal, 373, 446–457.
25. Gu, X., Wang, Y., Lai, C., Qiu, J., Li, S., Hou, Y., Martens, W., Mahmood, N., Zhang, S. 2015. Microporous bamboo biochar for lithium-sulfur batteries. Nano Research, 8(1), 129–139.
26. Gul, S., Whalen, J.K., Thomas, B.W., Sachdeva, V., Deng, H. 2015. Physico-chemical properties and microbial responses in biochar-amended soils: Mechanisms and future directions. Agriculture, Ecosystems and Environment, 206, 46–59.
27. Hays, D., Patrick, J.W., Walker, A. 1976. Pore structure development during coal carbonization. 1. Behaviour of single coals. Fuel, 55(4), 297–302.
28. Henning KH, D.J. 1991. Aktivkohlen – Herstellungsverfahren und Produkteigenschaf- ten. (Vortrag im Rahmen des Seminars.A ktivkohlen in Technik und Umweltschutz" der Technischen Akademie Wuppertal am 18, u. 19, April 1991).
29. Schmid H.P. 2012. 55 Uses of Biochar, Ithaka Journal 1/ 2012: 262–264.
30. Izquierdo, M.T., Rubio, B., Mayoral, C., Andrés, J.M. 2003. Low cost coal-based carbons for combined SO2 and NO removal from exhaust gas. Fuel, 82(2), 147–151.
31. Jindo, K., Mizumoto, H., Sawada, Y., Sanchez-Monedero, M.A., Sonoki, T. 2014. Physical and chemical characterization of biochars derived from different agricultural residues. Biogeosciences, 11(23), 6613–6621.
32. Katyal, S., Thambimuthu, K., Valix, M. 2003. Carbonisation of bagasse in a fixed bed reactor: Influence of process variables on char yield and characteristics. Renewable Energy, 28(5), 713–725.
33. Krull, E.S., Baldock, J.A., Skjemstad, J.O., Smernik, R.J. 2012. Characteristics of biochar: Organo-chemical properties, Biochar for Environmental Management: Science and Technology, 53–65.
34. Lee, J., Kim, K.H., Kwon, E.E. 2017. Biochar as a Catalyst. Renewable and Sustainable Energy Reviews, 77, 70–79.
35. Lee, J.M., Park, D.G., Kang, S.S., Choi, E.J., Gwon, H.S., Lee, H.S., Lee, S.I. 2022. Short-Term Effect of Biochar on Soil Organic Carbon Improvement and Nitrous Oxide Emission Reduction According to Different Soil Characteristics in Agricultural Land: A Laboratory Experiment. Agronomy, 12(8).
36. Lehmann, J., Joseph, S. 2012. Biochar for environmental management: Science and technology. Biochar for Environmental Management: Science

and Technology.

37. Leng, L., Huang, H. 2018. An overview of the effect of pyrolysis process parameters on biochar stability. Bioresource Technology, 270, 627–642.
38. Lewandowski, W.M., Radziemska, E., Ryms, M., Ostrowski, P. 2011. Modern methods of thermochemical biomass conversion into gas, liquid and solid fuels. Ecological Chemistry and Engineering, S, 18(1), 39–47.
39. Li, C., Bair, D.A., Parikh, S.J. 2018. Estimating potential dust emissions from biochar amended soils under simulated tillage. Science of the Total Environment, 625, 1093–1101.
40. Li, S., Harris, S., Anandhi, A., Chen, G. 2019. Predicting biochar properties and functions based on feedstock and pyrolysis temperature: A review and data syntheses. Journal of Cleaner Production, 215, 890–902.
41. Li, X., Peng, B., Liu, Q., Zhang, H. 2022. Microwave pyrolysis coupled with conventional pre-pyrolysis of the stalk for syngas and biochar. Bioresource Technology, 348.
42. Li, Y., You, S. 2022. Biochar soil application: soil improvement and pollution remediation, Biochar in Agriculture for Achieving Sustainable Development Goals, 97–102.
43. Liu, J., Shen, J., Li, Y., Su, Y., Ge, T., Jones, D.L., Wu, J. 2014. Effects of biochar amendment on the net greenhouse gas emission and greenhouse gas intensity in a Chinese double rice cropping system. European Journal of Soil Biology, 65, 30–39.
44. Liu, R., Sarker, M., Rahman, M.M., Li, C., Chai, M., Cotillon, R., Scott, N.R. 2020. Multi-scale complexities of solid acid catalysts in the catalytic fast pyrolysis of biomass for bio-oil production – A review. Progress in Energy and Combustion Science, 80.
45. Liu, W.J., Jiang, H., Yu, H.Q. 2015. Development of Biochar-Based Functional Materials: Toward a Sustainable Platform Carbon Material. Chemical Reviews, 115(22), 12251–12285.
46. Lu, C., Zhang, X., Gao, Y., Lin, Y., Xu, J., Zhu, C., Zhu, Y. 2021. Parametric study of catalytic co-gasification of cotton stalk and aqueous phase from wheat straw using hydrothermal carbonation. Energy, 216.
47. Lua, A.C., Yang, T., Guo, J. 2004. Effects of pyrolysis conditions on the properties of activated carbons prepared from pistachio-nut shells. Journal of Analytical and Applied Pyrolysis, 72(2), 279–287.
48. Lyu, H., He, Y., Tang, J., Hecker, M., Liu, Q., Jones, P.D., Codling, G., Giesy, J.P. 2016. Effect of pyrolysis temperature on potential toxicity of biochar if applied to the environment. Environmental Pollution, 218, 1–7.
49. Malińska, K., Zabochnicka-Świątek, M., Dach, J. 2014. Effects of biochar amendment on ammonia emission during composting of sewage sludge. Ecological Engineering, 71, 474–478.
50. Matovic, D. 2011. Biochar as a viable carbon sequestration option: Global and Canadian perspective. Energy, 36(4), 2011–2016.
51. Mimmo, T., Panzacchi, P., Baratieri, M., Davies, C.A., Tonon, G. 2014. Effect of pyrolysis temperature on miscanthus (Miscanthus × giganteus) biochar physical, chemical and functional properties. Biomass and Bioenergy, 62, 149–157.
52. Méndez, A., Terradillos, M., Gascó, G. 2013. Physicochemical and agronomic properties of biochar from sewage sludge pyrolysed at different temperatures. Journal of Analytical and Applied Pyrolysis 102, 124–130.
53. Naeem, M.A., Khalid, M., Arshad, M., Ahmad, R. 2014. Yield and nutrient composition of biochar produced from different feedstocks at varying pyrolytic temperatures. Pakistan Journal of Agricultural Sciences, 51(1), 75–82.
54. Nigussie, A. 2012. Effect of Biochar Application on Soil Properties and Nutrient Uptake of Lettuces (Lactuca sativa) Grown in Chromium Polluted Soils, Kissi, Endalkachew, Conference Proceedings.
55. Novak, J.M., Busscher, W.J. 2013. Selection and use of designer biochars to improve characteristics of southeastern USA coastal plain degraded soils, Advanced Biofuels and Bioproducts, 69–96.
56. Pak, N.M., Rempillo, O., Norman, A.L., Layzell, D.B. 2016. Early atmospheric detection of carbon dioxide from carbon capture and storage sites. Journal of the Air and Waste Management Association, 66(8), 739–747.
57. Peng, X., Ye, L.L., Wang, C.H., Zhou, H., Sun, B. 2011. Temperature- and duration-dependent rice straw-derived biochar: Characteristics and its effects on soil properties of an Ultisol in southern China. Soil and Tillage Research, 112(2), 159–166.
58. Prasad, M., Chrysargyris, A., McDaniel, N., Kavanagh, A., Gruda, N.S., Tzortzakis, N. 2020. Plant nutrient availability and pH of biochars and their fractions, with the possible use as a component in a growing media. Agronomy, 10(1).
59. Qambrani, N.A., Rahman, M.M., Won, S., Shim, S., Ra, C. 2017. Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: A review. Renewable and Sustainable Energy Reviews, 79, 255–273.
60. Ravi, S., Sharratt, B.S., Li, J., Olshevski, S., Meng, Z., Zhang, J. 2016. Particulate matter emissions from biochar-amended soils as a potential tradeoff

to the negative emission potential. Scientific Reports, 6.

61. Ribas, A., Mattana, S., Llurba, R., Debouk, H., Sebastià, M.T., Domene, X. 2019. Biochar application and summer temperatures reduce N2O and enhance CH4 emissions in a Mediterranean agroecosystem: Role of biologically-induced anoxic microsites. Science of the Total Environment, 685, 1075–1086.
62. Roskill. 2017. Activated Carbon: Global Industry, Markets and Outlook to 2025: 2017. Roskill Information Services Ltd. United Kingdom.
63. Rangabhashiyam, S., Paramasivan, B. 2019. The potential of lignocellulosic biomass precursors for biochar production: Performance, mechanism and wastewater application—A review. Industrial Crops and Products, 128, 405–423.
64. S.S. 2019. Piroliza odpadów jako element gospodarki o obiegu zamkniętym. Waste pyrolysis as part of a circular economy closed, Monografia s. 211, wyd. Politechniki Śląskiej. (in Polish)
65. Sahu, D., Kannan, G.M., Vijayaraghavan, R. 2014. Carbon black particle exhibits size dependent toxicity in human monocytes. International Journal of Inflammation, 2014.
66. Schenker, M.B., Pinkerton, K.E., Mitchell, D., Vallyathan, V., Elvine-Kreis, B., Green, F.H.Y. 2009. Pneumoconiosis from agricultural dust exposure among young California farmworkers. Environmental Health Perspectives, 117(6), 988–994.
67. Shackley, S., Carter, S., Knowles, T., Middelink, E., Haefele, S., Sohi, S., Cross, A., Haszeldine, S. 2012. Sustainable gasification-biochar systems? A case-study of rice-husk gasification in Cambodia, Part I: Context, chemical properties, environmental and health and safety issues. Energy Policy, 42, 49–58.
68. Sing, K.S.W., Everett, D.H., Haul, R.A.W., Moscou, L., Pierotti, R.A., Rouquerol, J., Siemieniewska, T. 1985. Reporting Physisorption Data for Gas/Solid Systems with Special Reference to the Determination of Surface Area and Porosity. Pure and Applied Chemistry, 57(4), 603–619.
69. Singh, B., Singh, B.P., Cowie, A.L. 2010. Characterisation and evaluation of biochars for their application as a soil amendment, Australian Journal of Soil Research, 516–525.
70. Singh, H., Northup, B.K., Rice, C.W., Prasad, P.V.V. 2022. Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: a meta-analysis. Biochar, 4(1).
71. Sohi, S.P. 2012. Carbon storage with benefits. Science, 338(6110), 1034–1035.
72. Song, W., Guo, M. 2012. Quality variations of poultry litter biochar generated at different pyrolysis temperatures. Journal of Analytical and Applied Pyrolysis, 94, 138–145.
73. Steiner, C., Das, K.C., Melear, N., Lakly, D. 2010. Reducing nitrogen loss during poultry litter composting using biochar. Journal of Environmental Quality, 39(4), 1236–1242.
74. Suman, S., Gautam, S. 2017. Pyrolysis of coconut husk biomass: Analysis of its biochar properties. Energy Sources, Part A: Recovery, Utilization and Environmental Effects, 39(8), 761–767.
75. Sun, J., He, F., Pan, Y., Zhang, Z. 2017. Effects of pyrolysis temperature and residence time on physicochemical properties of different biochar types. Acta Agriculturae Scandinavica Section B: Soil and Plant Science, 67(1), 12–22.
76. Sun, J., Lian, F., Liu, Z., Zhu, L., Song, Z. 2014. Biochars derived from various crop straws: Characterization and Cd(II) removal potential. Ecotoxicology and Environmental Safety, 106, 226–231.
77. Syuhada, A.B., Shamshuddin, J., Fauziah, C.I., Rosenani, A.B., Arifin, A. 2016. Biochar as soil amendment: Impact on chemical properties and corn nutrient uptake in a Podzol. Canadian Journal of Soil Science, 96(4), 400–412.
78. Thabelo, M. 2018. Biochar and poultry manure effects on selected soil physical and chemical properties and maize (Zea mays) in a dry environment, University of Venda.
79. Tripathi, M., Sahu, J.N., Ganesan, P. 2016. Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. Renewable and Sustainable Energy Reviews, 55, 467–481.
80. Trompowsky, P.M., De Melo Benites, V., Madari, B.E., Pimenta, A.S., Hockaday, W.C., Hatcher, P.G. 2005. Characterization of humic like substances obtained by chemical oxidation of eucalyptus charcoal. Organic Geochemistry, 36(11), 1480–1489.
81. Tsuji, K., Shiraishi, I. 1997. Combined desulfurization, denitrification and reduction of air toxics using activated coke: 1. Activity of activated coke. Fuel, 76(6), 549–553.
82. Walker Philip L.Jr., J., L. Figueiredo, J.A.M. 1986. Carbon and Coal Gasification. [NATO ASI Series 105]. Science and Technology (1986, Springer Netherlands).
83. Wang, J., Wang, S. 2019. Preparation, modification and environmental application of biochar: A review. Journal of Cleaner Production, 227, 1002–1022.
84. Wang, X., Xing, B. 2007. Importance of structural makeup of biopolymers for organic contaminant sorption. Environmental Science and Technology, 41(10), 3559–3565.
85. Wang, Z., Liu, G., Zheng, H., Li, F., Ngo, H.H., Guo, W., Liu, C., Chen, L., Xing, B. 2015. Investigating the mechanisms of biochar's removal of lead from solution. Bioresource Technology, 177, 308–317.

86. Xie, T., Reddy, K.R., Wang, C., Yargicoglu, E., Spokas, K. 2015. Characteristics and applications of biochar for environmental remediation: A review. Critical Reviews in Environmental Science and Technology, 45(9), 939–969.
87. Xu, Y., Qi, F., Bai, T., Yan, Y., Wu, C., An, Z., Luo, S., Huang, Z., Xie, P. 2019. A further inquiry into co-pyrolysis of straws with manures for heavy metal immobilization in manure-derived biochars. Journal of Hazardous Materials, 380.
88. Yang, X., Meng, J., Lan, Y., Chen, W., Yang, T., Yuan, J., Liu, S., Han, J. 2017. Effects of maize stover and its biochar on soil CO_2 emissions and labile organic carbon fractions in Northeast China. Agriculture, Ecosystems and Environment, 240, 24–31.
89. Zhao, N., Lv, Y.Z., Yang, X.X., Huang, F., Yang, J.W. 2018. Characterization and 2D structural model of corn straw and poplar leaf biochars. Environmental Science and Pollution Research, 25(26), 25789–25798.
90. Zhao, S., Yang, P., Liu, X., Zhang, Q., Hu, J. 2020. Synergistic effect of mixing wheat straw and lignite in co-pyrolysis and steam co-gasification. Bioresource Technology, 302.
91. Zielińska, A., Oleszczuk, P. 2016. Effect of pyrolysis temperatures on freely dissolved polycyclic aromatic hydrocarbon (PAH) concentrations in sewage sludge-derived biochars. Chemosphere, 153, 68–74.
92. Zulkornain, M.F., Shamsuddin, A.H., Normanbhay, S., Md Saad, J., Ahmad Zamri, M.F.M. 2022. Optimization of rice husk hydrochar via microwave-assisted hydrothermal carbonization: Fuel properties and combustion kinetics. Bioresource Technology Reports, 17.