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Review

Biochar as a Multifunctional Component of the Environment—A Review

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Abstract: The growing demand for electricity, caused by dynamic economic growth, leads to a decrease in the available non-renewable energy resources constituting the foundation of global power generation. A search for alternative sources of energy that can support conventional energy technologies utilizing fossil fuels is not only of key significance for the power industry but is also important from the point of view of environmental conservation and sustainable development. Plant biomass, with its specific chemical structure and high calorific value, is a promising renewable source of energy which can be utilized in numerous conversion processes, enabling the production of solid, liquid, and gaseous fuels. Methods of thermal biomass conversion include pyrolysis, i.e., a process allowing one to obtain a multifunctional product known as biochar. The article presents a review of information related to the broad uses of carbonization products. It also discusses the legal aspects and quality standards applicable to these materials. The paper draws attention to the lack of uniform legal and quality conditions, which would allow for a much better use of biochar. The review also aims to highlight the high potential for a use of biochar in different environments. The presented text attempts to emphasize the importance of biochar as an alternative to classic products used for energy, environmental and agricultural purposes.

Keywords: biochar; pyrolysis; environmental conservation; soil ameliorant

1. Introduction

In recent years, biochar and the wide range of its possible applications have been extensively investigated by researchers worldwide. In accordance with the definition specified by the International Biochar Initiative (IBI), biochar is a fine-grained product of carbonization, characterized by a high content of organic carbon and low susceptibility to degradation, which is obtained through the pyrolysis of biomass and biodegradable waste [1]. It is produced from organic matter as a result of pyrolysis, a process which is carried out in the absence of oxygen. Biochar can be utilized for energy-related purposes associated with environmental conservation and agriculture. The wide range of biochar applications is continuously expanding, mainly in such areas as industry, agriculture and operations related to the natural environment. It can be used as a soil additive, or added to fodder and silage, or applied in water treatment [2,3]. Biochar can also be used for the immobilization of contaminants from soil, and in sewage treatment; it can be applied as a supplementary material in composting and in methane fermentation processes [4–9]. Biochar application can be used as a filter for tar reduction in pyrolysis and gasification, as a fuel when pelletized, and also used as a substrate to produce hydrogen [10–12].

One of the ways to convert biomass is the gasification process, a state-of-the-art method of energetic use of biomass. The advantages of this process in relation to other methods are the possibilities of multi-directional use of the obtained product, namely the gas. Modern gasification methods make it possible to obtain two products: synthesis gas (syngas) being a mixture of gases (H_2, CO, CO_2, CH_4) and residues in the form of ash. When classifying gasification processes, they can be divided using different criteria depending on reactor type, gasification factor, thermal relations, gasification process parameters (pressure, temperature). The first stage of the gasification process is drying the material, which can have up to 50% water content, at a temperature of 100–200 °C. The next step is pyrolysis at increased temperatures (200–600 °C) using an anaerobic atmosphere to release the volatile parts contained in biomass. Products of this stage are solid substances such as charcoal, liquid substances (tars, oils and gas water), flammable gas and aromatic hydrocarbons such as benzene, toluene. The last stage is gasification (temperature above 750 °C) of solid and liquid substances produced at pyrolysis. This is a series of exo- and endothermal reactions that result in the production of flammable gas components [13–15]. Thermal processes of biomass (mainly the ones of lignocellulosic origin) processing also include torrefaction. The process is carried out in an anaerobic atmosphere at a temperature of 200–300 °C and the rate of temperature increase is in the range of 10–100 °C min^{-1}. Given the long duration of the process and relatively low temperatures, this process is also called roasting or mild pyrolysis [16]. Biomass processed as a result of the torrefaction process acquires new physicochemical properties, especially important when used as a fuel for the power industry. Products of torrefaction are characterized by increased milling susceptibility and energy density and their properties resemble low calorific coals. A typical torrefaction process is characterized by loss of mass and chemical energy of the raw material used. When analyzing the mass/energy ratio, an increased concentration of chemical energy of the fuel obtained in relation to the raw material can be observed [17]. When analyzing environmental aspects, biochemical conversions have an important role. The products (fuels) produced by these technologies are biogas, thio-alcohols and biodiesel. The use of biochemical processes seems reasonable when biomass contains large amounts of water. One type of such transformation is alcoholic fermentation, which allows carbohydrates to be broken down under anaerobic conditions with the addition of yeasts. The product of this conversion is bioethanol. Liquid biofuels can also be produced using a biochemical process such as oil esterification, which makes it possible to obtain methyl esters. Methane fermentation, on the other hand, affects the decomposition of multi molecular organic substances under conditions of limited access to oxygen. In the results, we obtain products in the form of alcohols, lower organic acids, as well as methane and carbon dioxide [18].

Thermal biomass conversion methods include pyrolysis, i.e., thermochemical transformation of biomass occurring in anaerobic conditions or in the presence of a small amount of oxygen, insufficient for combustion. Pyrolysis generates carbonization products, i.e., a highly carbonized solid biomass substance, bio-oil, also referred to as pyrolysis oil, as well as gas [19]. Depending on the parameters applied we can distinguish slow (bio-carbonization), fast and moderate pyrolysis as well as gasification. Fast pyrolysis (temperature of 500 °C with the peak (ultimate) temperature maintained for 1 s) produces approximately 12% of biochar. Slightly better results can be achieved by using moderate pyrolysis (temperature of 500 °C, the ultimate temperature maintained for 10–20 s)—approximately 20% of biochar. The highest percentage of biochar, at a level of 35%, may be obtained with the use of slow pyrolysis (at a temperature of 400–500 °C with the ultimate temperature maintained for 5–30 min.). The application of a high temperature, over 800 °C, and a short duration of the process at the ultimate temperature (gasification) leads to a yield of biochar amounting to 10% [20,21]. The low biochar content may also be related to the presence of oxygen and water in the reactor. It should also be pointed out that by using the rate of biomass heating as a classification factor we can distinguish between fast and slow pyrolysis. Reference books state that the heating rate of 1–100 °C min^{-1} is used in slow pyrolysis, whereas reaching the temperature heating rate above 1000 °C min^{-1} is characterized as fast pyrolysis [22].

The properties of biochar closely depend on the temperature of the pyrolysis process [23]. An increase in the temperature of pyrolysis leads to greater carbonification of the feedstock resulting in a higher carbon content and a decrease in the contents of hydrogen and oxygen [24]. The process of pyrolysis optimization towards obtaining a desired product should take into account the temperature of the reactor, rate of temperature increase, and duration of the process at the ultimate temperature. The authors emphasize relevant parameters of pyrolysis optimization in order to increase the utility of biochar as a high carbon material and at the same time cheap in production and generally available for application. This review presents an interdisciplinary approach to the topic of the importance of biochar in environmental, legal aspects of its application and quality standards.

2. Biochar and its Properties

Biochar may be produced from numerous materials of varied origins, e.g., energy crops, forest residues as well as agricultural residues [25–30]. Other materials used for biochar production include sewage sludge, waste from the food processing industries, e.g., oats previously subjected to fermentation, as well as poultry litter and cattle manure (Table 1) [31,32]. Importantly, the choice of feedstock for biochar production depends on e.g., economic and logistic factors as well as the parameters of the pyrolysis process itself and the types and properties of the applied substrates, e.g., water contents [21].

Table 1. Selected feedstocks used in biochar production [25–30].

Origin of Feedstocks	Type
Agriculture	Energy crops, corncob, rice husk, sunflower husk, post-fermentation oats, bamboo, bagasse, waste from olive oil production, straw, wheat husk, cattle manure, poultry litter
Forest	Conifer bark, pellets from sawdust, peat, moss, beech timber,
Waste	Waste from tea factories, paper, sewage sludge, municipal organic waste

The most important properties of biochars include their chemical composition, stability, specific surface and porosity. Importantly, the chemical composition of biochars mainly depends on the chemical composition of the substrates used in biochar production. Biochars contain stable organic carbon, aromatic compounds, aliphatic compounds and ash [33]. Taking into account the type of biomass and parameters of thermal processing applied, the content of carbon in biochar may be in the range of 50–90%, water 1–15%, volatile substances up to 40% and mineral substances up to 5%. Carbonization products have a neutral or alkaline pH and are highly resistant to microbiological degradation and decomposition; applied in the soil they are stable in terms of their chemical composition [21]. Their porous structure on the other hand contributes to improved sorption capacity of soils (Figure 1) [34].

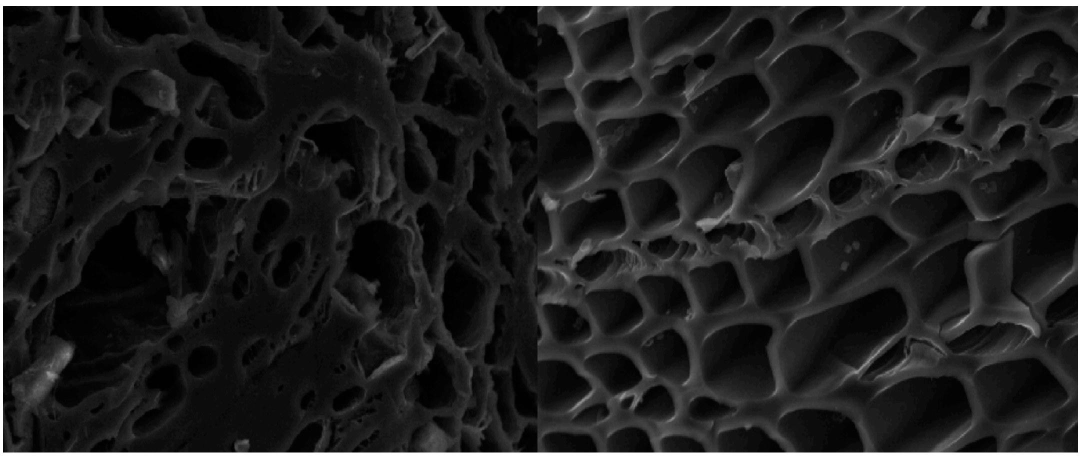

Figure 1. The porous structure of biochar [35].

Biomass pyrolysis conducted at higher temperatures may lead to an increased pH of the biochar. At lower temperatures it is possible to obtain biochar with higher ion-exchange capacity. Because of their physicochemical properties, biochars can be used for such purposes as soil carbon sequestration, the production of soil conditioner, as well as soil rehabilitation [21]. Table 2 presents some selected properties of biochars in relation to the feedstocks used and pyrolysis temperature applied.

Table 2. Selected properties of biochar, depending on the materials applied and the temperature of the pyrolysis process.

Feedstock for Biochar Production	pH	C g kg^{-1}	N g kg^{-1}	C/N	P g kg^{-1}	K g kg^{-1}	Ash %	Temp. of Pyrolysis (°C)	References
Acacia bark	7.4	398	10.4	38	–	–	–	260–360	[36]
Coconut	–	690	9.4	73	–	–	3.38	500	[37]
Corn	–	675	9.3	73	–	10.4	–	350	[38]
Corn	–	790	9.2	86	–	6.7	–	600	
Green waste	6.2	680	1.7	400	0.2	1	–	450	[39]
Peanut shells	–	499	11.0	45	0.6	6.2	–	400	[40]
Pecan shells	7.6	834	3.4	245	–	–	3.8	700	[41]
Pecan shells	–	880	4.0	220	–	–	–	700	[42]
Rice straw	–	490	13.2	37	–	–	9.54	500	[37]
Sewage sludge	–	470	64	7	56	–	35	450	[43]
Sugarcane bagasse	–	710	17.7	40	–	–	4.34	500	[37]
Eucalyptus wood	7.0	824	5.7	144	0.6	–	0.23	350	[44]
Oak wood	–	759	1.0	759	–	1.1	–	350	[38]
Oak wood	–	884	1.2	737	–	2.2	–	600	

Different types of fuel, including waste, can be used for pyrolysis. The types of raw materials for pyrolysis can generally be divided into three groups: mine fuels, e.g., coal, biomass, e.g., wood, sewage sludge and plastics, e.g., tires. Each of these raw materials has different chemical composition and physical properties, which affect the quality of the pyrolysis products obtained. Biomass is a very universal raw material in its morphology and physical characteristics. Biomass material can be partially wet or dry, homogeneous or heterogeneous, of high density or of a loose structure, low or high ash content, high or low fragmentation [45]. This variety of properties of raw materials for biofuel production in gasification reactors is difficult and it is necessary to apply other processing measures focusing on the properties in question. Hence there is a large diversity of bioreactors used in biomass processing as well as a wide range of final products diversified in terms of properties determined by the conditions of the pyrolysis process and the type of bioreactor. Knowledge of the chemical structure and their behavior during the process of pyrolysis is extremely important from the point of view of application of optimal technological solutions, selection of appropriate parameters (temperature, process duration), process efficiency and environmental nuisance.

High heating rates promote cellulose and hemicellulose depolymerization reactions, minimizing the volatiles residence time inside the particle and secondary reactions. It also favors the volatiles cracking. So, the condensable gas release goes on quickly thus achieving high yields of bio-oil and the lowest production of char. Low temperatures and low heating rates promote intra-chain hydrogen bonds of cellulose functional groups, increasing the probability of collision to produce a dehydration reaction. For high heating rates, inter-chain hydrogen bonds are stronger achieving greater separation between the cellulose molecules and thus decreasing the possibility of collisions that facilitate the dehydration reaction. There are many reports in literature pointing out the importance of the effects of the heating rate on the yields of bio-oil and char [22,46,47].

The physical and chemical properties of the raw materials used in the process are the most important. The highest yields of carbonization products are obtained when raw materials with high lignin content are subjected to pyrolysis at moderate temperatures. Basically, biomass containing a significant amount of volatile substances offers a large amount of pyrolytic gas and bio-oil, and the presence of solid coal increases the efficiency of biochar production [19]. The moisture content of biomass has a significant impact on the heat transfer process and product distribution. Numerous experiments in the process of pyrolysis have confirmed that carbonization product's efficiency increases at low heating rates. During fast heating, the efficiency of volatile parts increases and less secondary reactions occur [48]. In the case of reactors with a high biochar production capacity, the fixed bed reactor and fast-moving fluidized bed reactors should be considered. In the case of slow pyrolysis, the use of a fixed bed allows the use of a large working surface of the reactor. Fluidized beds allow the process to be carried out much faster but are limited by volume for technological reasons [49].

3. Legal Aspects and Quality Standards

The term "biochar" does not appear in the legislation of the EU or Poland. The only European country which has adopted regulations relating to it is Switzerland. Considerations linked to biochar production and the wide range of its possible applications should however take into account the legal regulations on waste management, use of fertilizers and product safety [2].

Legal regulations fail to explicitly define the status of biochar, classifying it as a product, by-product, or waste [50–53]. In practice, biochar is perceived as waste, while in the literature it is most frequently described as a by-product of pyrolysis. The relevant EU and Polish regulations [54] define waste as "any substance or object which the holder discards, intends to discard or is required to discard". In accordance with the Waste Act, biochar produced from agricultural biomass wastes, or bio-wastes, may be classified as waste material produced as a result of a thermal conversion process. Accordingly, carbonization products should be treated as waste, however, biochar is not listed in the waste catalogue [55]. Article 14 of the Waste Act provides that "specific types of waste no longer have the status of waste if, following recovery, including recycling, they jointly meet specified conditions:

- the object or substance is commonly used for particular purposes,
- there is a market or demand for such objects or substances,
- the object or substance meets the technical requirements for applications related to specific purposes as well as the requirements set out in the rules and standards applicable to the product,
- use of the object or substance does not lead to negative consequences for human life or well-being or for the environment, as well as the requirements defined by regulations of the European Union" [56]. Given the above, biochar is no longer classified as waste.

In light of the regulations biochar can also be classified as a by-product, if it meets all of the following conditions: "further use of the object or the substance is certain; the object or substance may be used directly with no further processing other than normal industrial practice; the object or substance is produced as an integral part of a production process; the substance or object fulfils all relevant requirements, including legal, product-related, environmental and health protection requirements for the specific use of these substances or objects and their use will not lead to overall adverse environmental or human health impacts" [56]. Biochar can also be treated as a product, if it is the main product of a given process, and it has been produced from biomass obtained specifically for this purpose [53]. In a situation when biochar is treated as a product or by-product, the provisions of the Waste Act are not applicable; on the other hand, it is necessary to take into account other legal requirements (e.g., the regulations of the registration, evaluation, Authorization and restriction of chemicals (REACH) system) [57].

As regards EU laws, it can be concluded that the use of biochar in soils is not explicitly regulated or forbidden [53]. As an exception, Switzerland permits the use of biochar in agriculture provided that the requirements specified by the European Biochar Certificate (EBC) are complied with. The use of biochar as a soil ameliorant in the EU is subject to the provisions set forth by Regulation (EC) No 2003/2003 [58]. In Poland, in order to use biochar as a fertilizer or soil ameliorant it is necessary to complete a registration procedure and obtain approval from the Minister of Agriculture and Rural Development. Notably, these legal requirements are not applicable if biochar is used as a fertilizer in quantities necessary for experimental studies as well as in research and development projects [2].

Given the wide range of substrates used in the production of biochar, as well as the diverse conditions of thermal processing applied, and consequently the varied chemical composition of the final products, attempts have been made to regulate quality requirements related to carbonization products. It was necessary to take adequate steps and develop uniform guidelines and define quality requirements for biochar and substrates used in its production. As a result, global biochar organizations developed their own quality standards (biochar quality certificates):

- Biochar standards defined by the International Biochar Initiative (IBI), USA [1];
- European Biochar Certificate defined by the European Biochar Foundation [59];
- Biochar Quality Mandate developed by the British Biochar Foundation in the United Kingdom [60].

These standards present recommendations related to the substrates applied in the production of biochar, parameters of technological processes, requirements for biochar materials introduced into the soil as well as providing guidelines for the methodology of conducting measurements and analyses. Importantly, the requirements contained therein take the form of guidelines and they are not legally binding in the European Union member states [61]. Developed under the European Union Framework Program, the project entitled REFERTIL (reducing mineral fertilizers and chemicals use in agriculture by recycling treated organic waste as compost and biochar products) was designed to develop quality requirements for biochar to be adopted as recommendations for legal regulations relating to fertilizers [62].

The quality requirements defined for biochar ensure the safety of its soil-related applications, specify permissible contents of heavy metals, furans, polychlorinated biphenyls, dioxins and polycyclic aromatic hydrocarbons [63–65]. Table 3 summarizes and compares permissible levels of contaminants in biochar, as defined by the International Biochar Initiative (IBI), British Biochar Foundation (BQM), European Biochar Foundation (EBC) and under the REFERTIL project.

Table 3. The permissible content of contaminants in biochar, based on the existing quality standards [1,59,60,62].

Parameter (mg kg^{-1} of Dry Matter)	IBI	BQM		EBC		REFERTIL
		Type of Biochar				
		High Grade	Standard	Premium	Basic	
As	13–100	10	100	13	13	10
Cd	1.4–39	3	39	1	1.5	1.5
Cr	93–1200	15	100	80	90	100
Cu	143–6000	40	1500	100	1000	200
Hg	1–17	1	17	1	1	1
Ni	47–420	10	600	30	50	50
Pb	121–300	60	500	120	150	120
Zn	416–7400	150	2800	400	400	600
Se	2–200	5	100	–	–	–
Mo	5–75	10	75	–	–	–
F	–	–	–	–	–	–
WWA	6–300	20	20	4	12	6
PCB	0.2–1	0.5	0.5	0.2	0.2	0.2
Dioxins and furans (ng kg^{-1})	20	20	20	20	20	20

In Poland, the requirements related to the permissible contamination of organic and organic–mineral fertilizers, as well as crop enhancers are defined by the Regulation of the Minister of Agriculture and Rural Development of 18 June 2008 on the implementation of certain provisions of the Act on fertilizers and fertilization [66]. It specifies e.g., permissible contents of cadmium, lead, nickel, mercury, respectively at the levels of 5, 140, 60, 2 mg kg^{-1} of dry matter of the fertilizer or crop enhancer, yet it fails to take into account contaminations taking the form of polycyclic aromatic hydrocarbons or polychlorinated biphenyls.

4. Biochar in Environmental Conservation

The use of biochar in environmental protection falls within the scope of remediation of polluted soils, energy production, climate change aspects, waste management, sustainable development issues. Production of biochar is one of the methods permitting the reduction of the need for the disposal of animal and plant waste. Biodegradable animal waste, agricultural biomass and sewage sludge can be effectively used for the production of energy through pyrolysis. Additional benefits include a reduction in the volume of waste subjected to thermal processing, as well as the elimination of pathogenic microorganisms potentially occurring e.g., in cattle manure and sewage sludge. The use of the above waste material in the production of biochar may also lead indirectly to the reduction of methane emissions from landfills and reduce the necessity of seeking alternative methods of waste management [67].

Increased emissions of CO_2 to the atmosphere in recent years have led to a significant disproportion between the natural emission and absorption of carbon. It is necessary to take action to balance carbon in the atmosphere by its capture and storage e.g., in the soil [68]. One of the solutions to this problem involves the use of biochar obtained from various types of biomass. Introduced into the soil, it enables the long-term sequestration of carbon. According to the literature, by adding biochar to soil at a rate of 13.5 t ha^{-1} it is possible to store the carbon within it for a minimum of two hundred years [69]. Furthermore, it has been shown that biochar may lead to a decrease in emissions of nitrous oxide (N_2O) and methane (CH_4) from the soil, mediated by biotic and abiotic mechanisms [70].

One of the main applications of biochar is its use as a renewable fuel [71–73]. Carbonization products can be incinerated or co-incinerated in combined heat and power plants and power plants. Biochar in comparison with raw biomass contain less of significant amounts of chlorine, and volatile substances influencing the reduction of boiler efficiency and increased emission of inorganic particles. Changes in chlorine content result from the specificity of the pyrolysis process. During pyrolysis, the chlorine contained in the raw biomass is released in gaseous form and goes to the environment. These changes result from the changing structure of the material and the processes of degassing biomass. Inorganic compounds forming fine particles result in increased sludge production in fuel-burning boilers. This problem disappears in the moment of carbonization of a fuel, which is particularly important in the processes of biomass combustion. Biochar is therefore an important element in reducing this disadvantage [74]. Such fuels are an alternative to conventional fossil fuels (Table 4), as well as they offer the possibility of recovering energy from waste deposited in landfills [2]. An additional direction of wide use of biochar in the power industry is the acquisition of many energy products during its production. Additionally, obtained electricity and heat may successfully reduce the costs of the process and creation of cogeneration installations, which may become an important element in the creation of local power grids. Such small installations on the local market quickly and efficiently process e.g., waste from agricultural production, which creates independent power systems essential for the elimination of power and climate risks [33].

Table 4. The calorific value and contents of carbon, ash and volatiles in selected fuels and biochars [2,26,75,76].

Fuel	Calorific Value (MJ kg^{-1})	Carbon	Ash	Volatiles
			%	
	Fossil fuels			
Natural gas	48.0	75.0	0.0	100.0
Lignite	25.0	60.0	12.0	25.0
Bituminous coal	7.5–21.0	66.0–73.0	10.0–20.0	40.0–60.0

Table 4. *Cont.*

Fuel	Calorific Value (MJ kg^{-1})	Carbon	Ash	Volatiles
			%	
Biomass				
Wood	10.5	35.0	1.0	55.0
Straw	15.0	43.0	3.0	73.0
Rapeseed	15.3	44.7	7.3	78.7
Sunflower	15.7	17.2	8.3	74.5
Biochar				
Biochar from rapeseed	23.4	72.7	21.8	13.6
Biochar from sunflower	20.5	63.4	28.9	13.4
Biochar from oil palm (residues)	17.1	53.8	3.1	81.9
Biochar from cherry wood	27.7	59.5	9.1	22.2

Owing to their sorption properties, biochars can effectively immobilize contamination from solid, liquid and gaseous media. Of particular note is that more effective sorption properties are to be found in biochars produced at higher temperatures, since they have larger specific surface and higher microporosity. Research conducted so far shows that biochars can be used as sorbents in processes aimed at immobilizing the residues of pharmaceuticals and bacteriostatic antibiotics, e.g., sulfamethoxazole, from sewage [28,77], as well as heavy metals from aqueous solutions, municipal sewage and industrial wastewater [78–81]. It has also been reported that biochar was used for immobilizing such pesticides as carbaryl, atrazine, simazine and acetochlor from soils [82–84]. Because of their physicochemical and structural properties, carbonization products are an alternative to activated carbon and other treatment technologies applied to various substances, including sewage and wastewater [77]. Table 5 presents possible biochar applications for immobilizing various types of contaminants in soil and water.

Table 5. Possible biochar applications for immobilizing contaminants in soil and water.

Contamination	Type of Biochar (Feedstock/Pyrolysis Temperature)	Type of Environment	References
Agricultural chemicals			
Atrazine	Cattle manure (450 °C)	Soil	[85]
	Cattle manure (200 °C)	Water	[86]
Atrazine and simazine	Green waste (450 °C)	Water	[82]
Pentachlorophenol	Bamboo (600 °C)	Soil	[87]
Antibiotics			
Sulfamethazine	Hardwood (600 °C)	Water	[88]
Sulfamethoxazole	Bamboo (450 and 600 °C)	Water	[28]
Tylosin	Hardwood (850 and 900 °C)	Water	[89]
Tetracycline	Rice husk (450–500 °C)	Water	[90]
Other hydrocarbons			
Pyrene	Corncob (600 °C)	Water	[91]
	Sawdust (400 i 700 °C)		[92]
Trichloroethylene	Peanut shell (300 and 700 °C)	Water	[93]
Naphthalene	Pine needles (100–700 °C)	Water	[94]
Heavy metals			
Cadmium	*Miscanthus sacchariflorus* (300–600 °C)	Water	[95]
Aluminum	Rice straw (100–600 °C)	Water	[29]
Lead	Pine wood (300 °C)	Water	[96]

5. Biochar as a Activated Carbons

In recent years there has been an increase in interest in the use of active coals resulting mainly from their low production cost and favorable physicochemical properties, which include a strongly developed specific surface, very good ion-exchange properties and high mechanical and chemical durability. In general, any material which contains carbon in its composition in organic compounds may be used to produce active carbons. The raw materials used, activation process, and process parameters determine the physical properties and performance characteristics of the resulting carbon. Modifying these activation properties determines the porosity and pore volume distribution in the carbon. Activated carbon is defined as a carbonaceous material with a large internal surface area and highly developed porous structure resulting from the processing of raw materials under high temperature reactions. It is composed of 87–97% carbon but also contains other elements depending on the processing method used and raw material it is derived from. Activated carbon's porous structure allows it to adsorb materials from the liquid and gas phase. On an industrial scale, the precursors of active carbons include mainly fossil coals, wood, peat, and coconut shells. The literature presents information concerning the production of activated carbons by activating a variety of waste materials such as nut shells, sawdust, straw, fruit stones, straw, sewage sludge and many others [97]. These activities are of justified environmental character as they manage a significant amount of waste and their economic aspect is important as well. The studies carried out so far have highlighted the fact that activated carbons produced from waste materials can show a better sorption capacity than products made from traditional precursors. For example, carbons were prepared from combination of the waste tea and K_2CO_3 have high surface area and pore volume [98]. The production of active carbons takes place within two mechanisms, i.e., physical activation and chemical activation. Physical activation, also known as thermal activation, consists of two successive stages. The first step is the pyrolysis of the starting material, carried out at a high temperature (usually 500–1000 °C). During the second step, the carbonization product obtained is activated by exposure to a high temperature (800–1000 °C) using an oxidizing agent such as water vapor, carbon monoxide (IV) or a mixture of these gases. If the above-mentioned stages of physical activation take place at the same time, then it is direct activation process. In the process of chemical activation, the precursor is subjected to high-temperature treatment in an inert gas atmosphere after prior impregnation or mixing with an activating agent. The activators used in chemical activation are mainly potassium and sodium hydroxide, sodium and potassium carbonates, zinc chloride, and phosphoric acid (V). The disadvantage of this method is its high cost caused by the necessity to use expensive activating agents and to introduce a stage aimed at removing the excess of the activating agent and the by-products. The physical and chemical properties of active carbons such as porous structure, highly developed specific surface area or sorbent capacity are strictly dependent on the substrates used, activation methods and conditions of the process. The properties of carbon sorbents can also be significantly altered by means of appropriate chemical modifications both during the manufacturing process and after the activation process. These processes consist mainly of the introduction of functional groups into the structure of the carbon material or on its surface, which significantly change its chemical character. Modification of carbon materials can be carried out using e.g., liquid oxidants, to which we include, primarily HNO_3, H_2O_2 and $(NH_4)_2S_2O_8$. The surface of active carbons can also be modified with various types of organic and inorganic compounds, e.g., pyridine, compounds of platinum, of chromium, of silver, of copper, of potassium, of zinc, of sodium and of cobalt. This type of modification is aimed at obtaining materials with significantly increased and selective sorbent capacity. Table 6 presents the surface area values for physically and chemically activated carbons obtained from different materials [99–102].

Table 6. Surface area values for physically and chemically activated carbons obtained from different material.

Physically Activated Carbons			Chemically Activated Carbons		
Initial Material	Activation Agent	Surface Area$^{m2\ g-1}$	Initial Material	Activation Agent	Surface Area$^{m2\ g-1}$
Rice [103]	Steam	1122	Rice [104]	KOH	3263
Peanut shells [105]	Steam	757	Hazelnut shells [106]	KOH	1700
Cornstarch [107]	Thermal	686	Corncob [108]	KOH	3054

Table 6. *Cont.*

Physically Activated Carbons			Chemically Activated Carbons		
Grape pomace, grape stalks [109]	Steam	266 300	Grape seeds [110]	KOH	1860
Finish wood [111]	CO_2	590	Eucalyptus wood, Beech wood [112]	KOH	2120, 2460
Olive Stone [113]	CO_2	1355	Olives stones [114]	$ZnCl_2$	1860
Sunflower stem [115]	CO_2	438	Stem of date palm [116]	KOH H_3PO_4	947 1100
Vine shoots [117]	CO_2	1173	Waste tea [98]	K_2CO_3	1722

Activated carbons can be used in many sectors e.g., pharmaceutical, food industrial as additives or the emerging use. A series of studies demonstrated that activated biochar could be available for pharmaceuticals removal, such as acetaminophen, caffeine, atrazine, diclofenac, glyphosate, naproxen, ibuprofen and sulfamethazine [118]. Hoegberg et al. conducted a study to identify the maximum adsorption capacities of amitriptyline and paracetamol, separately and in combination, to activated charcoal [119]. The rapid adsorption tendencies of activated carbon have also extended the biochar applications to biomedical sciences. Activated carbons or activated charcoal have shown their functionalities in preventing gastrointestinal absorption of certain toxins and drugs, thereby enhancing their elimination even after systemic absorption [120]. Ozsoy and van Leeuwen in their study focused on decolorizing solutions of waste fruit candy extract dissolved in deionized water using activated carbon adsorption. The aim of this study was to use activated carbon in treatment methods for candy wastes to facilitate reuse of fruit pulp, sugar and organic acids in the process and minimize the wastes emanating from this industry [121].

Biochar-mediated adsorption of organic contaminants may be based on the principle of electrostatic interactions with polar or non-polar groups (Figure 2) [122–124].

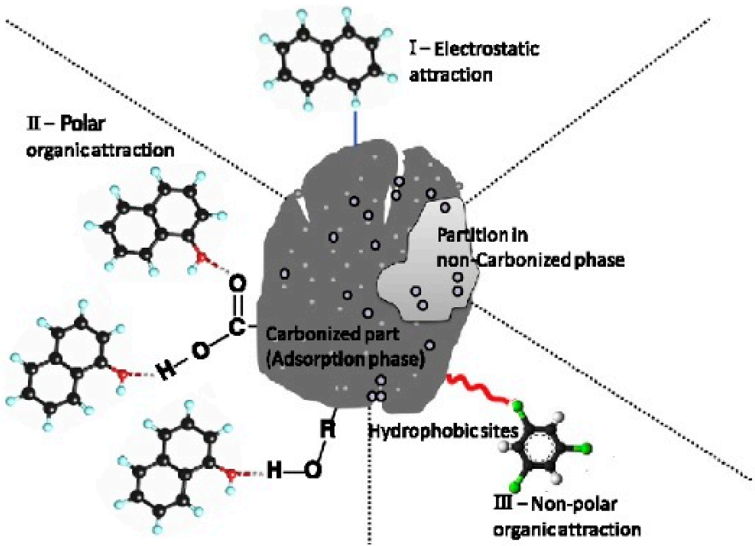

Figure 2. Mechanisms of organic substance adsorption on the surface of carbonization products [124].

Adsorption of inorganic contaminants, including ions of heavy metals, through the use of biochar is characterized by four mechanisms:

- ion exchange (Na^+, K^+ ions are involved),
- precipitation,
- anionic metal attraction,
- cationic metal attraction (Figure 3) [122,124,125].

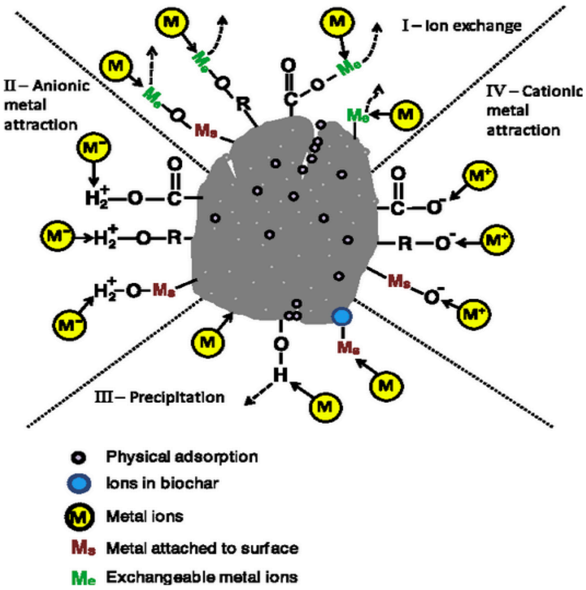

Figure 3. Types (mechanisms) of metal ion adsorption on the surface of carbonization products [124].

Mechanisms I and IV are identical normal cation exchange reactions, albeit with metal cations at I, and H^+ at IV.

In view of the numerous beneficial properties of biochars, in particular the high contents of organic carbon, these materials can be used to enhance the physicochemical and biological properties of soils [126].

6. Biochar as Soil Conditioner

Interest in biochar as a potential soil enhancer began with the discovery of preta de Indio—Indian black earth (in Amazonia), notable for its high content of carbon and nutrients [127]. As shown in previous research, the soils were created a few thousand years ago as a result of the burning of forests and natural fires, as well as soil improvement with the use of charcoal applied by pre-Columbian natives [128].

From the agricultural point of view, the application of carbonization products for soil amelioration seems to be beneficial because the treatment improves the conditions for plant growth, leading to a better yield (Figure 4, Table 7) [129]. Furthermore, due to the rapid effects and relatively low costs of such treatment, biochars are more and more frequently used in processes of soil remediation and conservation [130].

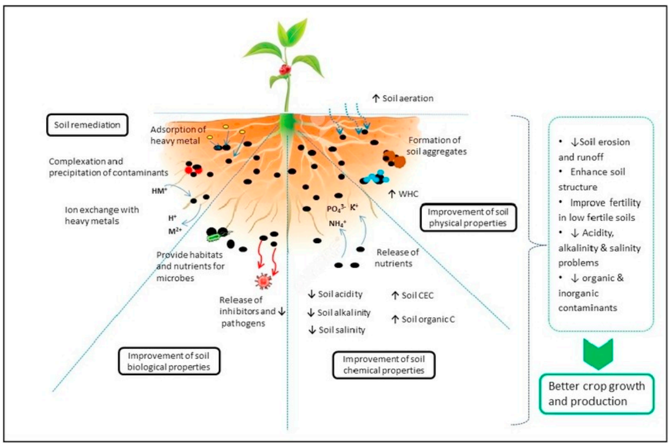

Figure 4. Influence of biochar on soil properties [131].

Table 7. Effect of biochar application on the yield of selected plants.

Type of Biochar (Feedstock)	Dose (t ha^{-1})	Crop	Increase in Yield Compared to the Control %	References
Wood	68	Cowpea	20	[132]
	136.75	Cowpea	100	
	68	Rice	50	
Poultry litter	10	Radish	42	[39,133]
	50.5	Radish	96	
Woodchips from fruit trees	22	Grapes	20	[134]
Cattle manure	15	Maize	150	[135]
Hardwood	19	Maize	10	[136]
	38		17	
	58		48	
Wheat straw	40	Rapeseed	36	[137]
	40	Sweet potatoes	54	

The activity of biochar, after it is introduced into the soil environment, depends predominantly on the feedstocks used in its production and the parameters of the pyrolysis process. These determine the contents of macro- and micro-elements as well as harmful substances, such as e.g., heavy metals. The heterogeneous chemical composition of biochars enables their interactions with a large variety of organic and inorganic compounds present in the soil [138]. The diverse properties of biochar materials enable reactions with mineral and organic fractions of soil and the accumulation of combined mineral and organic complexes [139]. Biochars introduced to the soil are characterized by a high stability and resistance to biological decomposition, therefore they are recognized as a highly effective medium for the sequestration of carbon dioxide in soil [33]. Moreover, the application of biochars to soil leads to increased contents not only of carbon but also of other biogenic compounds, such as phosphorus, potassium, magnesium and nitrogen [39,140]. Owing to their large ion-exchange capacities and specific surface, biochars also produce such effects as the reduced leaching of biogenic elements from soils and a decreased emission of nitrous oxide [141]. Recent study has highlighted that crop biochar also contains biogenic silica (phytoliths) and can quickly release bioavailable silicon to enhance plant biomass and promote the biological silicon cycle in soil [142]. One of the functions of the biocarbon addition is to modify the nitrogen and phosphorus cycle. Biochar as an additive to soils has the ability to store nitrogen by increasing NH_3 and NH_4^+ retention, reducing N_2O emissions and eluting NO_3 ions, as well as inducing the development of nitrogen bacteria which directly affects the increase in soil productivity. Biochar is characterized by very different potassium contents, depending on the type of batch material used in production. Of all macronutrients present in carbonates, potassium is the best available element for plants, and the proportion of biosorptive forms is up to 95% of the total content [33]. Biochar fertilizers also lead to increased soil pH [143]. The related research has shown that carbonization products contain numerous alkaline substances, e.g., calcium carbonate, which may affect soil reaction, and the best effects, i.e., the highest pH increase, may be achieved in strongly acidified soils. Increased pH which is beneficial in acid tropical soils like terra preta but reduces yield in soils of high pH as in many temperate regions [41,144]. Biochar also impacts the physical properties of soil by improving its water retention, capacity to form aggregates, and resistance to erosion [145]. The improvement of the physical characteristics of soils resulting from the use of biochar as a soil ameliorant mainly depends on the properties of the biochar, and these are predominantly determined by the technology applied in its production [146,147]. Owing to their highly porous structure, carbonization products may create favorable conditions for microorganisms, as a consequence improving the fertility and productivity of soils (Table 8). For example, biochar addition to the soil with a high oil organic matter level leads to higher microbial stimulation and consequent higher N mineralization [148].

Table 8. Effects of biochar application on the soil environment of soil microorganisms.

Type of Biochar (Feedstock)	Impact on Soil Microorganisms	References
Willow wood and swine manure: slow pyrolysis at 350 °C slow pyrolysis at 700 °C	Increased microbial biomass in both cases: increased dehydrogenase activity decreased dehydrogenase activity	[149]
Poultry litter and pine woodchips (pyrolysis at 400 and 500 °C)	Increased microbial biomass	[150]
Leaves and fragmented branches	Increased rate of fungal and bacterial growth	[151]
Wood (fast pyrolysis)	Increased microbial count	[152]

7. Conclusions

The research conducted so far focusing on the characteristics and possible applications of biochar in a way attempts to regulate the flow of inorganic matter in the environment and provides significant support for the conservation of the natural environment, in particular taking into account the phytoremediation and utilitarian dimension of sustainable energy management.

Owing to their physicochemical properties, biochars may be used for such purposes as carbon sequestration in soils, reduction of the bioavailability of contaminants affecting living organisms as well as water treatment. They also present significant potential for the immobilization of heavy metals from aqueous solutions and for reducing their mobility in soils. In recent years there has been an increase in interest in the use of activated carbons with elevated and selective sorption capacity. Literature describe important role the waste products as a substrate for the production of such sorbents. Pyrolysis process of biomass allows produce high quality fuel in biochar form. Such fuels are an alternative to conventional fossil fuels, as well as they offer the possibility of recovering energy from waste deposited in landfills.

According to the latest research, the application of carbonization products may effectively enhance the physicochemical properties of soils and improve the fertility of poor soils. Biochar, as a product of thermal biomass conversion carried out with a reduced availability of oxygen, is characterized by a high content of carbon and excellent sorption properties. From the point of view of agriculture, the application of biochar as a soil conditioner produces numerous benefits, such as the enhancement of the physical, chemical and biological properties of soils, and this contributes to an increased crop yield. The application of biochar in soils may be an alternative to traditional forms of mineral amendment and strengthens the ecological aspect of bioenergy engineering.

Continuous progress in research on the use of biochar, its production methods and characterization techniques allow us to conclude that biochar technologies, especially as a means of improving the quality of soil or sorbent of pollution from soil and water, will become much more important in the future. However, it should be stressed that due to the lack of specific regulations for biochar, its commercial use is limited. In order to develop the biochar industry and ensure environmental safety, uniform legal and quality regulations should be ensured.

It should, however, be emphasized that further comprehensive research is needed to investigate the feasibility of the application of biochar and to determine the optimum methods for using this highly productive material.

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