The use of Biochar made from Biomass and Biosolid as a Substrate for Green Infrastructure

M. Novotný[1], M. Marković[2], J. Raček[1], T. Chorazy[1], P. Hlavínek[1]

[1]Brno University of Technology, Faculty of Civil Engineering, AdMaS, Purkyňova 651/139, 612 00 Brno, Czech Republic, novotny.m3@fce.vutbr.cz, racek.j@fce.vutbr.cz, chorazy.t@fce.vutbr.cz, hlavinek.p@fce.vutbr.cz
[2]University of Banja Luka, Faculty of Agriculture, Bulevar Vojvode Petra Bojovica 1A, Banja Luka 78000, RS, Bosnia and Herzegovina, mihajlo.markovic@agro.unibl.org
Presenting author email: hlavinek.p@fce.vutbr.cz

Abstract: In the European Union, current waste and wastewater management is energy demanding and produces many residues or products that can only partially be used/recycled. This paper evaluates the use of biochar made from biomass and biosolids as a substrate for green infrastructure, city parks, green parking lots, and especially green roofs and walls, which are nowadays replacing the ordinary roofing while considered an eco-friendlier solution in urban planning. Because of the existence of different kinds of biochar (made from different feedstocks e.g. sludges, biomass, municipal solid waste, wood, plant residues, etc.), different chemical and physical properties may occur while application; e.g. retention of nutrients, absorption of pollutants and harmful gases, carbon sequestration or improvement of pH of amended soil. Results of the review consider the usage of biochar as a substrate for green infrastructure in pursuance of its characteristics, limiting pollutants concentration, and potential benefits and risks for the environment, water sources and occurring climate change. Since biochar has a positive influence on plant growth and rainwater capturing, its use as a substrate is the main objective of this research paper. The review is based on the analysis of different existing research and case studies related to biochar management, from which the impact of biochar on substrate characteristics, water retention and quality of runoff from green roofs will be elucidated.

Keywords: blue-green infrastructure, green roof, biomass, biosolids, biochar

1 Introduction

This paper aims to advance the wastewater management system and biodegradable waste management towards the circular economy paradigm and sustainability as targeted in The European Green Deal, one of the Commission priorities for 2019-24 [1]. The use of raw sources including water is increasing with the growing population which has an impact on the accruing production of wastewater (WW) and its by-product after treatment - sewage sludge (SS) known also as biosolids. The increasing volume of SS is exceeding the limit capacities and the possibility of its further incineration, landfilling or reuse. Regulations for the member countries of Europe Union (EU) regarding the use of SS in agriculture are based on the Council Directive 86/278/EEC from 1986 [2]. Monitoring, usage and disposal of SS are based on the Council Directive 91/271/EEC from 1991 [3]. Both directives prescribe the protection of the environment and human health while using or disposing of the SS as their main aim. The increased quantity and production of SS and the limitation of its disposal lead to finding alternative solutions for its recycling and further usage. Similar process applies to other organic wastes mainly produced from food and agriculture sector, known as biomass. Reusable biomass includes waste from agricultural production, wood waste, animal manure, and biomass from biodegradable municipal waste. Almost all wastes of biological origin can be currently reprocessed and reused. Such an ecological circular system leads to a positive impact on the environment as well as ongoing climate change. In this paper we focus on biochar produced from food industry, paper and pulp production, straw waste, nuts shells, digested fish waste, animal manure and biosolids from SS.

Biochar is prepared by pyrolysis (combustion at low oxygen conditions) of biomass. The resulting solids are rich in carbon and other elements and when admixed to soil, several positive aspects occur such as improved nutrient retention, water retention, and control of contaminants. For this reason, the addition of biochar into soil is proposed as an appropriate strategy not only for soil quality improvement but also as a means for remediation of contaminated soils. Carbon storage in the form of biochar also contributes to the reduction of carbon dioxide (greenhouse gas) release. The use of biochar can therefore present an effective strategy to cope with the decreasing quality of agricultural land, the high demands on food self-sufficiency, the risks of soil contamination, and the threat of the greenhouse effect [4].

Green infrastructure (GI) is a key adaptation measure to climate change. It is a combined network of urban greenery and local rainwater management. In urban environment, GI combines technical solutions with natural principles into a functional whole [5]. An important prerequisite for healthy growth and resilience of urban greenery is the use of suitable substrates that are capable of high water retention due to porosity and at the same time provide a friendly environment for plant root growth [6]. Thanks to its unique properties, biochar becomes a key functional element of all substrates. Applications of biochar in soil of GI systems improves the soil properties. Biochar improves physical (e.g., water holding capacity, GHG removal and moisture level), chemical (e.g., pollutants immobilization and carbon sequestration), and biological (e.g., nutrients, microbial abundance, and diversity) properties of the soils [7] [8] [9].

2 Organic solid waste and biochar production

The process of biochar production with sufficient quality is based on pyrolysis of organic biodegradable feedstocks, which are usually found as various type of wastes or by-products. Each of them may have different physical and chemical properties which affect the final quality and beneficial characteristics of resulting biochar [10]. Several types of feedstocks can be used for biochar production; however, this review specifically describes biomass received from food industry, paper and pulp production, straw waste, nuts shells, digested fish waste, animal manure and biosolids, SS received from wastewater treatment plants (WWTPs).

Fig. 1 shows a scheme of biochar production and its use in green infrastructure. First, the input material is finely crushed and then pelletized, then the pellets are pyrolyzed and a biochar is formed. Biochar is then mixed into the substrate, which is used, for example, in green roofs, green walls and green car parks.

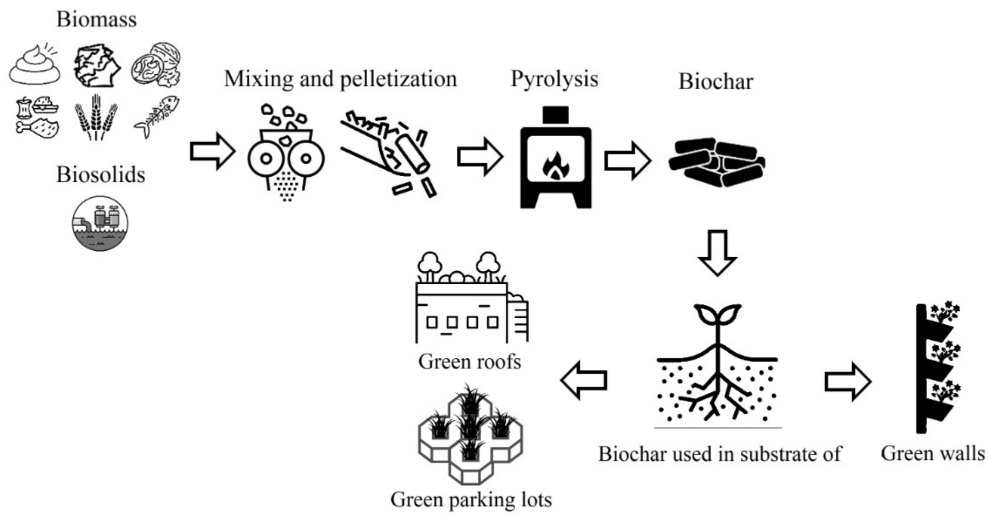

Fig. 1 Schema of biochar production and use in green infrastructure.

2.1 Biomass

According to Directive 2018/2001 [11] on the promotion of the use of energy from renewable sources, biomass is defined as the biodegradable fraction of products, waste and residues from agriculture, biological origin including plant and animal substances, from forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal wastes. Biomass waste is currently being disposed of mainly through landfill storing, incineration or composting as the cheapest and easiest option. According to the European Commission (EC), landfilling is the worst method of the disposal of biodegradable waste. This reason led to the adoption of the legislative proposal aimed at phasing out the disposal of recyclable wastes (including biowaste) in landfills, corresponding to a maximum landfilling rate of 10 % by 2035 [12], and the reduction of biodegradable waste in municipal landfills up to 30 % by 2025 [13].

Food waste

Food is an essential need for mankind; however, its residues became a worldwide challenge, that the planet environment is facing. According to the research project UNEP Food Waste Index 2021 [14], in 2019 a total of 931 million tons of food waste (FW) was generated, including food and inedible parts associated with food. This amount includes 61 % of FW from households, 26 % from service, 13 % from retail. FW is mainly composed of the following chemical substances: carbon, oxygen, nitrogen, lipids, proteins, carbohydrates, hemicellulose, cellulose, lignin, non-structural carbohydrates, starch, free sugar, sucrose and glucose. FW consisting of rice and vegetables is rich in carbohydrates, while FW from meat and eggs contains a large amount of protein and lipids [15]. Egg shells contain high levels of calcium carbonate ($CaCO_3$), which could be used as an alkaline compound to remove heavy metals (HM) from WW [16].

Paper waste

Paper production is the sixth-largest polluting industry from production sectors [17]. The production of paper waste (PW) and pulp mill residues increases year by year by the increased usage of paper-made products in different industrial areas [4]. According to Key statistic report of CEPI (2020) [18], the total amount of the paper, pulp and board production in 2020 were approximately 121.4 million tons while the total amount of paper collected and recycled was 54.5 million of tons. Europe's (27 member states of EU + Norway + Switzerland + United Kingdom) total PW and pulp recycling rate in 2020 was established to 73.9 %. Sludge generated by paper and pulp mill production contains large quantities of organic matter (OM) (60–94 %, e.g., cellulose or inorganic adhesives) and mineral fillers ($CaCO_3$ or aluminosilicate minerals), although, it includes less nitrogen and phosphorus in contrast to biosolids or compost. Therefore, nutrient addition is usually needed when PW is further used as a soil supplement in the agriculture sector [4] [19] [20].

Wallnut shells

Large quantities of shells from walnuts become a by-product residue considered as an agricultural waste every year worldwide. According to statistics from 2021 [21], the largest producer of walnuts is considered China. In 2021 the production of in-shell walnuts in China reaches 1.1 million metric tons. The main importers for Europe are considered the United States and Chile, while the main producers of walnuts in Europe are Romania, France, Spain and Italy [22].

Walnut shells (WSs) are part of the lignocellulosic waste biomass group. Lignocellulosic biomass consists of dry matter from plants or animal residues and is considered the most available material used for generation of energy materials, namely biofuel and bioethanol [23]. Lignocellulose is composed of carbohydrate polymers such as cellulose, hemicellulose and from lignin, aromatic polymer. Accordingly, WSs are considered to be a proper feedstock for further conversion into bio-valuable chemical and fuel products [24].

Straw waste

Straw, one of the most frequented biomass residues, is an agricultural by-product obtained after main product harvesting, generated and collected directly at the field, used as a feedstock in bio-based production or for other usage [25]. Straw wastes (SWs) are dry stalk residues of various cereals, including straws of wheat, rice, maize, barley, oats, rye, etc. The total residues production of listed SWs in the EU represented an abundant quantity of 294 million tons in 2013 [26]. The main biochemical composition of SW contains 28-39 % of cellulose, 23-25 % of hemicellulose and 15-25 % of lignin, lower per cent of ashes and proteins [27] [28].

Digested fish waste

Digested fish waste (DFW) has become an important and cheap source of bio-based production. Several alternative strategies have been developed to reduce large amount of DFW produced worldwide. Two different methods for improvement of economic value of DFW have been developed, namely mass transformation and sorting. Mass transformation includes conversion of DFW into fish meal, fish oil, fertilizers, etc. [29]. DFW is suitable for agricultural use owing to high contents of nutrients, such as N, P, and Ca [30]. According to the results of the research, Shikhaliyev et al. (2018) deducted that the cost-effective production, low metal content, and easily degradable character of biochar catalyst produced from DFW presents a potential catalyst for common industrial application [31].

Manure waste

A present decrease in the availability of ground for the production of crops is reflecting on the increase in animal production demand for mankind daily consumption. Hence, demand is likely to be met mainly through massive poultry and livestock production [32]. Manure produced by animals is an essential material used in agriculture due to the content of significant elements and nutritional value necessary for plant growth. Highest quantities of manure are mainly from poultry production and livestock. In EU is produced about 1 400 million tons of livestock manure [33]. Greater production of animal manure (AM) is associated with several additives in the feed including iron (Fe), cobalt (Co), arsenic (As), manganese (Mn) copper (Cu) and selenium (Se). Stated additives help to improve weight gain and reduce diseases, finally, they improve the generation of dairy and eggs. However, feed amendment rich in metals serve as a direct source of contamination [4] [34].

2.2 Biosolids

Biosolids, also known also as stabilized SS, is a by-product after the whole treatment process. The main composition of SS is water, OM and minerals. Treatment processes which remove solids in WWTPs include screenings and grit, naturally floating scum, and the removed solids during a primary and secondary treatment. SS is suitable for recycling and further reuse, mostly as soil amendment. SS, on the other hand, has become a term referred to untreated primary and secondary organic solids. The difference in terms between biosolids refers to the organic solids that have received stabilization treatment at WWTP, and the other types of sludges occurring in WW such as oils or gases that recycling to soil amendments is not acceptable. According to US EPA [35], SS comprises solids, semisolids, or liquid residue created during domestic treatment processes. SS includes domestic septage and solids removed during primary, secondary, or tertiary (advanced) treatment processes of WW or any substances derived from SS [35] [36].

Physical and chemical properties of biosolids mostly depend on technology and treatment process, also on the retention time in WW equipment. Composting, heat treatment, anaerobic digestion and lime addition are stabilization technologies for SS. The chemical composition of SS depends on the primary producers and varies with time and season. SS, following the stage of mechanical dewatering are masses presenting a lumpy structure and a bulk density within the range from 650 to 800 kg/m^3. The dry solid content of SS oscillates 2–12 % by weight and is one of their most important parameters when waste-to-energy management is considered [37] [38]. SS consist mainly of OM (usually more than 50 % of the dry matter), mostly hydrocarbons, amino-acids or lipids and with a small presence of lignin or cellulose [39]. Content of OM in SS from cities is higher but varies according to the treatment and conditioning carried out on the SS. It may be reduced, as an effect of dilution, by e.g., lime addition. OM presented in SS can lead to improvement of physical properties of soil, including the soil structure or attenuating the potential for surface runoff and erosion [37].

3 Biochar properties

The pyrolysis process greatly affects the qualities of biochar and its potential value to agriculture in terms of agronomic performance or in carbon sequestration. The process and its parameters, principally temperature and furnace residence time, are particularly important, however, the process and process conditions also interact with feedstock type in determining the nature of the product [40]. Pyrolysis is the thermochemical reductive process of converting biosolids into carbon rich solid product - biochar, having yield above 10–80 % carried out under a wide temperature range 100–1300 °C, at wide range of residence time 0.05 s–12 h under low or atmospheric pressure [41] [42]. Selected characteristics of biochar made from biomass and biosolids are noted in the Table 1.

Table 1 Chemical composition of biochar produced by pyrolysis under different temperatures of various feedstocks.

Feedstock	Max. process temperature (°C)	C (%)	H (%)	N (%)	O (%)	pH (-)	Ash (%)	Authors
Chicken manure	550	38.27	-	-	20.79	-	-	Jung et al., 2017 [43]
Chicken manure	750	24.7	0.67	-	16.30	-	-	Domingues et al. 2017 [44]
Pig manure	800	42.10	1.10	1.60	13.50	11.54	-	Tsai et al., 2012 [45]
Wheat straw	600	73.40	1.85	4.62	11.70	10.50	8.31	Katerina et al., 2017 [46]
Maize straw	600	29.00	1.07	1.22	23.90	10.20	44.90	Katerina et al., 2017 [46]
Barley straw	400	71.50	4.70	1.30	22.30	8.020	-	Kang et al., 2018 [47]
Rice straw	700	76.21	0.59	0.60	15.62	10.50	-	Guohua et al., 2016 [48]
Printing leaflets (art paper)	600	24.10	0.70	-	1.95	10.00	74.90	Xu et al., 2017 [49]
Paper sludge	650	41.35	2.05	3.52	8.98	10.31	-	Pariyar et al., 2020 [50]

Fishmeal	650	50.06	-	2.02	29.24	-	-	Shikhaliyeva et al., 2018 [31]
Food waste	550	63.13	2.92	2.77	16.00	9.92	-	Pariyar et al., 2020 [50]
Food waste	600	50.41	1.26	1.86	9.44	-	36.94	Liu et al., 2020 [51]
Walnut shell	900	55.30	-	0.47	-	9.70	40.40	Griffin et al., 2016 [52]
Walnut shell	550	48.98	6.10	0.38	44.54	-	3.72	Diao et al., 2021 [53]
Sewage sludge	600	7.75	1.74	0.69	0.94	-	-	Yuan et al., 2013 [54]
Sewage sludge	600	21.8	1.1	3.2	7.9			Xu et al., 2018 [55]

The certification of biochar and its commercial use is defined according to two main initiatives [56] [57]. Both certifications define biochar as a substance produced by thermal pyrolysis of biomass and biosolids under low oxygen conditions, allowing the use of SS and biomass from different sectors as the main feedstock.

The International Biochar Initiative (IBI) [56] standardized the definition and testing guidelines for biochar production further used as a soil amendment (IBI Biochar Standards) with the intent to provide stakeholders and commercial entities with the standards to identify certain qualities and characteristics of biochar, when it is used as a soil amendment. The IBI Biochar Standards are designed to support the IBI Biochar Certification Program. Biochar can be made from a variety of feedstocks, using a variety of different thermochemical conversion process of biosolids, and can possess many different attributes. The feedstock, unprocessed or processed, can be a combination of biomass and diluents but may not contain more than 2% by dry weight of contaminants, and any diluents that constitute 10 % or more by dry weight of the feedstock material must be reported as a feedstock component. Unprocessed feedstock types include rice hulls, straw, etc. and processed feedstock include different sorts of manure, SS, etc. IBI Biochar Standards identify three categories of tests for biochar materials: category A for basic utility properties (required for all biochar), category B for toxicant assessment and category C for advanced analysis and soil enhancement properties.

The European Biochar Certificate (EBC) [57] is a voluntary industry standard in Europe and in Switzerland, and it is obligatory when using the biochar in agriculture. EBC defines six different biochar grades: “Feed”, “AgroOrganic”, “Agro”, “Urban”, “ConsumerMaterials” and “BasicMaterials”. For gaining the European biochar certificate, EBC criteria must be met regarding the biosolids feedstock, the production method, the properties of the biochar and the way of application. For the purposes of this paper, we are only interested in groups “AgroOrganic” and “Agro” that meet all the requirements of the Regulation (EU) 2019/1009 laying down rules on the making available fertilising products on the market of EU and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 [58]. According to Appendix 1 Positive list of permissible biomasses for the production of biochar, it is possible to use SW and WS in both groups “AgroOrganic” and “Agro”. PW and FW can only be used as "Agro" if the plastic contamination does not exceed 1 % [59]. Pyrolysis of non-plant biomass such as SS, livestock manure, manure containing biogas digestates or bones and slaughterhouse waste can also produce valuable raw materials that could be used for bioeconomy and climate protection. In this sense, it is planned to include these raw materials in the mid-2022 list of EBC raw materials following a key review of the product safety verification and conditions of use.

Selected parameters for biochar certification according to guidelines of IBI [56] and EBC [57] are reported in Table 2, where the requirements are divided into biochar of category A and B (IBI) and "AgroOrganic" and "Agro" (EBC). For biochar of category A and "Feed" and "AgroOrganic" biochar the limits of selected parameters are stricter. The selected parameters are divided into main general parameters such as toxicant assessment, maximum allowed thresholds and other parameters. The first selected parameters of toxicant assessment are polycyclic aromatic hydrocarbon (PAHs), polychlorinated dibenzodioxins or dibenzofurans (PCDD/Fs), polychlorinated biphenyls (PCBs) and heavy metals (HMs): As, Cd, Cr, Cu, Pb, Hg, Ni and Zn. These selected parameters represent chemicals hazardous for agricultural use with respect to plants and organisms in the soil environment. The other parameters represent the indicators which improve the soil conditions. According to the guidelines, most other parameters require a declaration. Conversely, specific requirements are placed on the organic carbon C_{org}, the molar ratio $H:C_{org}$ and $O:C_{org}$.

Table 2 Selected parameters for biochar certification according to guidelines [56] [57].

	Selected parameter	Unit	Guidelines to biochar certification			
			International Biochar Initiative (IBI) [56]		**European Biochar Certificate (EBC)** [57]	
			Category A	**Category B**	**Agro Bio**	**Agro/Urban/Consumer Materials**
Toxicant assessment, maximum allowed thresholds	PAHs total	$mg \cdot kg^{-1}$ dry wt-mass	6	300	4	Agro: 6 Urban/Consumer Materials: Declaration
	PCDD/Fs		17	17	20	20
	PCBs*		0.2	1	0.2	0.2
	As		13	100	13	13
	Cd		1,4	20	0,7	1.5
	Cr		93	100	70	90
	Cu		143	6 000	70	100
	Pb		121	300	45	120
	Hg		1	10**	0,4	1
	Ni		47	400	25	50
	Zn		416	7 400	200	400
Other parameters	Moisture	%	Declaration		Declaration	
	C_{org}	%	≥ 60	≥ 30	Declaration	
	$H:C_{org}$	Molar ratio	0.7 maximum		0.7 maximum	
	Total ash	%	Declaration		Declaration	
	Total N	%	Declaration		Declaration	
	pH	-	Declaration		Declaration	
	Electrical conductivity	$dS \cdot m^{-1}$	Declaration		Declaration	
	Liming***	% $CaCO_3$	Declaration		-	
	Particle size distribution	%	Declaration		-	
	$O:C_{org}$	Molar ratio	-		0.4 maximum	
	Total P and K	$mg \cdot kg^{-1}$	Declaration		Declaration	

Available P	mg·kg^{-1}	Declaration	Declaration
Total Ca and Mg	mg·kg^{-1}	Declaration	Declaration
Available Ca and Mg	mg·kg^{-1}	Declaration	Declaration
S_{BET}	m^2·g^{-1}	-	Declaration

Notes: PAHs - polycyclic aromatic hydrocarbons total; PCDD/Fs - for dioxins/furans; PCBs - polychlorinated biphenyls; C_{org} - organic carbon; * PCDD/Fs in ng·kg^{-1}; ** methyl mercury 10 mg·kg^{-1} and inorganic mercury 40 mg·kg^{-1}; *** liming if pH is above 7.

Organic Carbon

One of the most important parameters of the biochar is the organic carbon (C_{org}) content . The C_{org} content depends mainly on the temperature of the pyrolysis process and the input feedstock [60]. At temperatures above 600 °C, carbonization takes place, thus removing all remaining non-carbon atoms and increasing the carbon concentration in the biochar [61]. The carbon content ranges from 35-95 % depending on the type of material [60] [57]. Pyrolyzed straw reaches values between 40-50 %, shells between 70-90 % [57]. The carbon content of pig manure biochar is between 40-60% based on several studies [45] [62] [63] [64]. According to Domingues et al. (2017) [44] the content of C_{org} in biochar produced from chicken manure decreases with increasing temperature, a similar trend can be observed in the case of Jung et al. (2017) [43]. Table 1 shows the percentage C_{org} of various feedstock.

Molar ratio H/C and O/C

The H/C molar ratio indicates the degree of carbonization, stability of biochar [57] and aromaticity of biochar [65] [66]. The H/C molar ratio value required by EBC [57] must be below 0.7. H/C depends on the temperature of pyrolysis process, with increasing temperature the atomic ratio decreased [65] [66]. According to the Table 1 the H/C molar ratio is in the following order of biosolids groups: manure < straws < PW < DFW < FW.

The O/C molar ratio can be used to indicate the hydrophilic nature of biochar, which vary according to biomass material and pyrolysis temperature [67]. Biochar with an O/C molar ratio of <0.2 is typically the most stable, possessing an estimated half-life of >1000 years; biochar with an O/C ratio of 0.2–0.6 have intermediate half-lives of 100–1000 years; biochar with an O/C ratio of >0,6 possess a half-life in the order of <100 years [68] [69]. The O/C molar ratio value required by EBC [57] should be below 0.4 which means approximately medium stability of the biochar. The O/C molar ratio is according to the Table 1 in the following order of biosolids groups: manure < straws < PW < DFW < FW < shells.

Bulk density

Bulk density is mass of a unit volume of a collection of particles or pieces. It is not an intrinsic property of the material, but depends on size, shape and compaction of the particles [8]. During the pyrolysis process, volatile substances are removed from the solid biomass structure and form a porous biochar structure. The higher the porosity, the lighter the char per unit volume becomes. Bulk density of biochar decreases with the higher treatment temperature [70] [71]. Omondi et. Al (2016) [72] compared bulk density of biochar from more than 100 studies with a focus on differentiation according to textural group, pyrolysis temperature, feedstock material and biochar rate. Most studies showed a reduction in bulk density on addition of biochar in spite of a few studies indicated increase in bulk density and it was attributed to the reorganization of particles as water drained to lower regions of the columns in lab experiments. The magnitude of the reduction of bulk density with respect to the used raw material of the biochar was found lower in the use of crop residue (8.5 %) than in manure waste (5.3 %).

pH

Most produced biochars are alkaline, however biochar can be produced at almost any pH between 4 and 12 [61]. Biochar produced at higher temperatures (>400 °C) usually has a higher pH than low temperature biochar (<400 °C) from the same feedstock [73]. The application of biochar could increase soil pH value. Many other factors depend on pH, such as CEC, ash content, nutrient availability and more [74]. Mengyuan et al. (2022) [75] reports that the pH of wood biochar is lower than that of crop residue and organic wastes. Table 1 shows the percentage pH of various feedstock.

Cation exchange capacity

Cation Exchange capacity (CEC) represents the amount of exchangeable cations (e. q. Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, NH^{4+}) [70]. CEC largely depends on the structure (i.e. porosity and specific surface area [70]) of the biochar and pH [76], presence of carboxyl functional groups [77]. The decrease in CEC with increasing temperature can be attributed to the loss of carboxyl functional groups during pyrolysis [61] [78]. The difference in values also concerns the age of the biochar, fresh biochar shows minimum CEC values [8] [61].

Specific surface area

The specific surface area (SSA) according to S_{BET} is an important characterization and comparison criterion for the physical structure of biochar. The S_{BET} is used to evaluate the gas adsorption data and generate a specific surface area result expressed in units of area per mass of sample (m^2/g) [57]. The SSA is most affected by the porosity and also the feedstock material. As the temperature increases, the pore volume in the biochar increases and thus the SSA also increases [79] [80]. Pores can be divided into three groups according to the standard of the International Union of Pure and Applied Chemistry (IUPAC): micropores (<2 nm), mesopores (2–50 nm), and macropores (>50 nm) [79]. The pyrolysis process degrades organic matter (cellulose, hemicelluloses, lignin) and thus creates a porous biochar structure, this is especially true at higher pyrolysis temperatures, therefore wood-biochar is offered as a better option with respect to higher SSA [80] [81].

4 Influence of biochar on substrate in blue-green infrastructure

4.1 Soil nutrition and fertility

Biochar made from waste materials is specific in that it contains many important elements for growing crops such as N, P, K, Ca and micronutrients, which should gradually release into the soil. This means that biochar may not contain significant amounts of nutrients immediately after application, but probably only in the long term [82]. The nutrient content of biochar depends on the raw feedstock materials and the pyrolytic conditions, e.g., temperature. Biochar derived from biosolids generally contain higher levels of N and P than those derived from wood and straw based feedstock materials [83] [84]. Furthermore, N content of biochar decreases with an increase in the pyrolytic temperature, due to conversion of parts of amino acids into pyridine-N and pyrrolic-N [84]. The presence of biochar increases the CEC of the soil by up to 40 %, which means participation in the retention of cations needed for plant nutrition. CEC values are mainly dependent on the biomasses and the temperature used in the pyrolysis process [44]. Increasing CEC in soil reduces nutrient leaching from the soil profile and increases nutrient availability to plant roots [83]. Nutrient leachability and subsequent infiltration of groundwater is also prevented, which could increase the use of fertilizers used [42].

The results of a study according to Hossain et al. (2011) [82] show that the concentrations of N and P in the form available for plant uptake are very low and depend on the process temperature. As the pyrolysis temperature increased from 300 °C to 700 °C, the total nitrogen content decreased by 55 %. This is due to the volatilization and loss of NH_4-N and NO_3-N fractions as volatile substances containing nitrogen groups. For phosphorus, increasing temperature had a positive effect on its amount, which increased. This proves that phosphorus is associated with the inorganic sludge fraction. Also, the concentration of all micronutrients (K, Ca, Fe, Mg, S) as total elements had an increasing character with increasing pyrolysis temperature [82]. The influence of pyrolysis temperature on the content of available nutrients N and P is also confirmed by Kookana et al. (2011) [85]. Biochar produced at 450–550 °C has a low content of available N, however, raw materials rich in N can retain up to 50 % of the original N even at low pyrolysis temperatures compared to wood-based biochar [85].

In their study, Chen et al. (2021) [86] achieved the increase of the phosphorus (P) and carbon (C) contents adding biochar made from SS. Compared to natural soil the increase of available nutrients was approximately 28–90 % and total nutrients approximately 28–115 %. The increase in nutrients N and P in the soil is also attributed to the high porosity and adsorption of the biochar; due to the retention of rainwater in the pores, it/biochar minimizes the leaching of nutrients from the soil.

At the Brno AdMaS research center, we test the use of biochar in green roof substrates. Already 4 months after installation, a visible difference between the two modules can be seen in Fig. 2. Biochar adds nutrients to the substrate and retains water, thus supporting the growth of Sedum in the right module.

Fig. 2 Comparison of green roof modules after 4 months from installation; left module without added biochar; right module with biochar.

4.2 Water holding capacity

Biochar added to the green roof (GR) substrate or when used in agriculture increases water retention capacity (WHC). WHC is the ability of a material to hold and retain water, depending on the total pore volume, SSA, pore structure, biomass source used and soil structure [70] [87] Increasing soil retention capacity with biochar is important for soils with a higher sand content, as water retention in these soils is low and water scarcity is critical for initial plant growth [88] [89]. Water retention in the soil is also important for stabilizing the soil environment and preserving the biological functions of the soil. Biochar with a higher SSA has a significant effect on WHC [63], the SSA of biochar increases with increasing pyrolysis temperature [70] The ability to retain water is related to the hydrophobicity of the biochar. In a biochar produced at a temperature above 400–500 °C, reactions occur that lead to a loss of hydrophobicity and the biochar becomes hydrophilic and can bind water [90] [70]. Higher hydrophobicity can be caused by compressed air in the pores, clogging of the pores with tars and oils that have not evaporated at lower temperatures. The better results for biochar formed at higher temperatures are probably due to the presence of an extended nanopore structure providing physical water adsorption [91]. Hydrophobicity of fresh biochar is due to the fact that it usually has large molecules with high density of H at the surface, however, some studies show that aging of biochar may increase hydrophobicity [92] [93], a similar effect can be achieved by oxidation of biochar surface at contact with air and water [89].

Influence at the quality and quantity of substrates in order to achieve increased rainwater retention without redundant roof weight is a key feature in optimizing the benefits achieved by installation of GR. The rate of WHC of GR depends on the amount of biochar added. It is recommended for GRs to have WHC between 35 and 65 % w/w [94]. According to their study, Cao et al. (2014) [95] added different amount of biochar made from green waste. The biochar dose was 0, 10, 20, 30 and 40 % w/w. By application of the maximum amount of biochar, i.e., 40 % w/w, the WHC increased by at least 74 % of the GRs substrate, relative to control GR with no biochar addition. Biochar also significantly reduced bulk density, with 40 % biochar substrates able to have an additional 1.5 cm/m^2 depth compared to the same weight as the control GR, which would further increase water retention. Beck et al. (2011) [96] added only 7 % w/w of a biochar made from rice hulls, pecan shells, WS, and coconut shells and found that water retention in the nearly saturated substrate increased by only 4.4 % [96]. During a four-year experiment, WS biochar significantly increased WHC by 25-28 % relative to control soil during the first two years, decreasing over the next two years to evaluate control soil [97].

Chen et al. (2018) [98] focused their study on biochar produced from SS by pyrolysis at 600 °C and proceeded with an experiment aimed at mixture of different amounts of biochar (5, 10, 15, 20 %) with natural soil and local natural soil as a substrate to GR with an average thickness of 25 cm. The substrates were analyzed as five individual samples. The received results showed that application of SS biochar may be an important amendment to GR substrate due to the increased WHC (up to 35 % depending on the rate of biochar) and prolonged permanent wilting point as well as water available for plants. Authors indicate the use of 15 % biochar was an optimal rate as soil improvement and suggest that biochar has excellent potential as an appropriate amendment to GR in order to improve the ecological benefits via exerting effects on the moisture, temperature and nutrients of roof substrates and further enhancing plant performance and altering microbial community [98].

4.3 Soil remediation

Soil remediation is a process in which pollutants come into contact with biochar in the soil and contaminants are adsorbed on its surface. By applying biochar to the soil, we can remove organic pollutants (antibiotics, pesticides, PAHs, PCBs, etc.), as well as inorganic substances known as heavy metals (Cu, Zn, Cd, Cr, Pb, Ni, Hg, etc.) [99] [100] [101] [102]. Biochar has many properties that support soil remediation, among them are e.g., high surface area, high carbon content, aromaticity, stability and CEC [99] [103] [104].

The amount of biochar added to the soil for heavy metal remediation varies in the studies and accounts for 0.5–30 % [105]. Metal ions are strongly adsorbed to specific active sites containing phenolic and carboxyl functional groups on the surface of biochar [101]. According to current research, the mechanisms of heavy metal removal by the addition of biochar can be attributed to electrostatic interactions, precipitation and other reactions [106] [107] [108] The incorporation of biochar into the soil increases the number of negative charges on the soil surface, due to the decreasing zeta potential and the increase in CEC [106]. Therefore, the electrostatic attraction between positively charged heavy metals and soil is enhanced. The reason for metal precipitation is the increase in soil pH resulting from the addition of biochar [107]. A number of studies have provided reliable data on the effectiveness of biochar in removing heavy metals from aqueous solutions and soil. Beesley et al. (2011) [109] used biochar and significantly reduced concentrations of Cd and Zn. The results of this study showed a threefold reduction of Cd concentration and a 45fold reduction of Zn concentration. Three-year monitoring by Bian et al. (2014) [110] of the effect of wheat straw biochar at application rates of 0, 10, 20, 30 and 40 t/ha had a positive effect on reducing the concentration of Cd and Pb. There was no significant difference between the application rates. The decrease in Cd concentration varied between years and ranged between 28–71 % and the decrease in Pb concentration was between 17–80 %. Immobilization of the Pb and Cd also occurred to cation exchange on the porous carbon structure.

Based on published data, the mechanism of organic pollutant removal can be described as surface adsorption and equilibrium distribution/partitioning. Adsorption refers in particular to surface interactions leading to the adhesion of pollutants to the surface of biochar, while sorption involves both surface adsorption and the equilibrium distribution of pollutant molecules in the micropores of biochar. Sorption takes place in relation to surface properties, such as SSA, micropore volume and pore size [111] [112].

Khan et al. (2015) found that the effectiveness of different biochar (application rate 5 %) was in order of peanut shell biochar (84 %) > soybean straw biochar (70 %) > rice straw biochar (55 %) > SS biochar (36 %), in terms of reducing PAHs bioaccumulation in turnip [113]. Influence of biochar from SS (application rate 10 %) according to Khan et al. (2013) [114] can reduce a total bioaccumulation of PAH concentrations in lettuce grown in contaminated soils by 58–63 %. Besides, adding 2 % biochar to the soils reduces the uptake of PCBs (especially for di-, tri-, and tetrachlorobiphenyls) by plants according to Wang et al. (2013) [115], total PCB concentrations in the roots of B. chinensis and D. carota are decreased by 61.5–93.7 % and 12.7–62.4 %, respectively. Atrazine is one of the most common pesticides, it is used as an herbicide against dicotyledonous weeds in the cultivation of corn, sugar cane, soybeans, etc. The addition of biochar from wheat straw in application rate 1 % to soil increased the efficacy of atrazine herbicide by 3,5 times and at the same time increased its persistence [116]. However, dairy manure biochar was effective in immobilizing atrazine and the effectiveness was enhanced with increasing incubation time and biochar rates. After 210 days, soils treated with the highest rate of 5 % biochar showed more than 77 % reduction in atrazine concentrations [117].

In the research center AdMaS is currently monitoring long-term use of the biochar in the substrate of the green parking lots. Three different types of parking places are shown in Fig. 3. The testing car park is monitored in terms of rainwater infiltration, load-bearing capacity and for the removal of oil substances during drips from cars.

Fig. 3 The testing green car park in research center AdMaS, Brno CR.

4.4 Carbon sequestration

Soil carbon sequestration is a process in which CO_2 is removed from the atmosphere and stored in the soil carbon pool. Continued increases in atmospheric CO_2 and global temperatures may have a variety of different consequences for soil carbon inputs via controls on photosynthetic rates and carbon losses through respiration and decomposition [102] [118]. Sequestration of C through the deposition of biochar in soil is one of the appropriate methods for mitigating the effects of climate change [119]. At higher pyrolysis temperatures, a more stable biochar is formed, but nevertheless the highest carbon sequestration has been found to be at 500 °C [120]. The stability of the biochar is affected by the H/C ratio; its low value (below 0.7) makes it difficult to decompose the biochar in the soil [121] [122]. The removal of CO_2 in GR takes place at two levels: the first is the direct removal of CO_2 in the leaf area of plants by means of photosynthesis and carbon storage in the substrate and plants. The second level is indirect CO_2 reduction by saving energy for heating and cooling buildings [123] [124]. Not only GR, but also grasslands in city parks, have great potential for storing carbon in the soil (approximately 25–150 g/cm^2/year) [124]. According to Woolf et al. (2010) [125], the global sustainable implementation of a biochar can compensate for a maximum of 12 % of current anthropogenic CO_2-C emissions. The optimal composition of the substrate and the thickness of the GR layer, along with a selection of plants has a very important role in the design of these structures. Properly designed GR design with these parameters in mind will, in the future, meet the performance in capturing and maximally storing carbon on the roofs. Shafique et al. (2020) [124] compared many studies focusing on carbon sequestration in GRs. The results show that GRs without the addition of a biochar has a storage potential of 0.3–9.8 kg C/m^2/year. In the study by Chen et al. (2018) [126], 10 % of the biochar was used in the GR growing medium at a substrate depth of 25 cm. According to the results, 9.33 kg C/m^2/year was deposited, and it was confirmed that biochar has a high potential for carbon storage due to its long-term stability [126].

4.5 Biochar for the mitigation of greenhouse gas emissions

Greenhouse gases (GHG) absorb solar energy and heat radiated from the earth's surface in the atmosphere. They capture them in our atmosphere and prevent this energy and heat from being released into space. There is a lot of GHG in the atmosphere naturally. The problem is that human activity adds a huge amount of them, which disproportionately increases the greenhouse effect, and contributes to global warming. The growing amount of GHG in the atmosphere means that average temperatures, including sea temperatures and ocean depths are rising due to a physical phenomenon called the greenhouse effect. The share of the most widespread emissions in the atmosphere is divided as follows: 82 % CO_2, 10 % CH_4, 5 % N_2O and 2 % HFC. The European Union has committed itself to reducing its GHG emissions by 20 % by 2020, 40 % by 2030 and 80 to 95 % by 2050 compared to 1990 [127].

Biochar in soil has the ability to effectively remove GHG [61] [104] [71], the main characteristics of biochar for GHG reduction includes surface area, functional groups, pore size, pore space, elemental composition, pH, and sorption sites. The presence of functional groups such as the carboxylic or hydroxyl groups on biochar surfaces can adsorb GHG, thus reducing their emissions when compared to unamended soil [128]. Biochar made from wood has shown a better ability to mitigate GHG compared to biochar made from animal waste and biosolids [122]. Biochar produced at higher temperatures (>600 °C) pyrolysis has been shown to be more efficient at removing N_2O [122], this is mainly attributed to high surface biochar, which provides more adsorption sites for nitrogen oxides, which reduces the reduction of these gases [104].

A very stable biochar will last in the soil for more than hundreds of years before it undergoes chemical and microbial decomposition, mainly due to its polycyclic aromatic structure [61] [129]. Biochar has been shown to have a very positive effect on GHG reduction, resulting in delayed CO_2, reduced N_2O, synthesis gas production as a substitute for fossil fuels for heat or electricity production, reducing the amount of fuel for growing or irrigating and reducing the production of nitrogen fertilizers with high GHG emissions [130] [131]. Gelardi et al. (2021) [103] compared observations from 88 studies that involved GHG mitigation, especially N_2O, and found that biochar in soil could remove N_2O by up to 32 %, but unfortunately this effect was not long-lasting and after a year the removal was negligible. Woolf et al. (2010) [125] estimated that the global implementation of biochar systems could reduce global GHG emissions by approximately 1.8 Gt CO_2 eq. per year, or 12 % of current anthropogenic

CO_2 eq., with a 50 % reduction due to C sequestration, 30 % from fossil fuel substitution and 20 % from eliminated CH_4 and N_2O emissions.

5 Discussion

This paper provides a review of the use of biochar made from biomass and biosolid as a substrate for GI. This review compares biochars from different types of feedstock, e.g. FW, paper and pulp production, straw waste, nuts shells, DFW, animal manure and SS. The influence of the biochar on the physical and chemical properties of the substrate in the GI depends mainly on the properties of the biochar, which are determined by the feedstock, pyrolysis temperature, pH, amount of C_{org}, O:C ratio, H:C ratio, bulk density, porosity, SSA, CEC, etc. The reviewed studies show an improvement in the soil properties of substrates when using biochar in GI, especially fertility, WHC, soil remediation, and mitigation of GHG. Biochar can long-term sequester carbon and thus reduce CO_2 from the atmosphere and improve economic and environmental applications with a focus on sustainability. Due its porous surface, biochar is suited for increasing the water holding capacity of soils. A wide range of elements important for crop cultivation are present in the biochar, such as N, P, K and micronutrients. Using biochar for environmental management and hazardous pollution remediation is desirable, especially in cities, in connection with car traffic (green parking lots). Further experiments need to be conducted to describe the effect of biochar feedstock source on the properties of soils.

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