Biochar Production Technologies and Applications

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Biochar is a carbon-rich amorphous and aromatic material that may present various interesting properties such as high hydrophobicity, alkaline nature, relevant concentrations of nutrients (N, P, and K), good water and nutrient retention capacities, low thermal conductivity, high energy content, and high superficial porosity that enable interaction with external organic and inorganic compounds. These properties are largely dependent on feedstock type and biochar production conditions. Although biochar is mostly recognized as a valuable resource for soil fertilization and conditioning, this material also has significant potential to be used for water filtration and remediation processes, as an animal feed supplement, for greenhouse gas (GHG) emission control (carbon sink feature), for insulation materials for the building sector, as an electrode material (for energy production and storage), cosmetic products, biogas production and improvement, and in catalytic processes.

Keywords: biochar ; applications ; biochar production

1. Biochar Production Technologies

Amongst the well-known carbonization processes, pyrolysis, gasification, hydrothermal carbonization (HTC), and torrefaction are generally employed to obtain biochar from several raw materials and for various types of applications.

Slow pyrolysis is a thermal conversion technology conducted at temperatures between 300–800 °C, aiming to maximize biochar yield. The process is performed at atmospheric pressure, and it is characterized by a relatively long residence time and low heating rates [1]. Different types of reactors have been used for biochar production via slow pyrolysis, such as agitated drum sand rotating kilns, wagon reactors, and paddle pyrolysis kilns. Moreover, in this process, high biochar yields are favored when using feedstocks with high lignin and ash content, along with large particle sizes. These characteristics improve biochar yield by increasing cracking reactions that reduce the amount of bio-oil (liquid products). On the other hand, fast pyrolysis offers particularly promising advantages in maximizing bio-oil yield (up to 75 wt.%), basically due to the very significant heating rates (over 200 °C/min) and shorter residence times [2].

Unlike pyrolysis, the gasification process is carried out in the presence of an oxidizing agent, and it is primarily used for syngas production (i.e., H_2, CO, CO_2, CH_4). As a result, biochar is considered a byproduct, and yields are low (<25%), resulting in limited research on the feasibility of biochar production [3][4].

Besides pyrolysis and gasification, torrefaction is an emerging approach for biochar production. In this process, moisture, CO_2, and O_2 contained in biomass are removed under inert conditions at 200–300 °C and long polysaccharide chains are depolymerized to produce a hydrophobic solid product with a low O/C ratio [5]. This process is generally operated with a slow heating rate; hence, it is also known as mild pyrolysis. Nonetheless, torrefaction is not considered a promising technique for biochar production, regardless of the higher product yields (70–80 wt.%), because torrefied biomass still contains a significant fraction of volatile components from raw biomass and the physical-chemical properties do not meet biochar requirements (e.g., O/C > 0.4). As a result, torrefaction is often used as a biomass pre-treatment process for moisture removal, feedstock densification, and increased brittleness [6].

Opposite to pyrolysis and torrefaction, which are carried out under a dry atmosphere, HTC proceeds in wet conditions and can also be referred to as wet pyrolysis or wet torrefaction. This process is performed in a biomass-water solution at temperatures of 180–300 °C and autogenous pressure (subcritical conditions) for several hours. Similar to pyrolysis, HTC presents significant biochar yields (50–80 wt.%), but also a liquid fraction composed of a bio-oil and water mixture (5–20 wt.%), and a gas phase that mainly includes CO_2 (2–5 wt.%) [7]. The great interest in HTC for biochar production is that the process can avoid the energy-intensive drying step that is usually required for conventional pyrolysis, and thus minimize operational costs. Also, HTC can convert feedstocks having >75 wt.% moisture content (diversifying feedstock options for biochar production) and decrease the leaching of salts and minerals, yielding biochars (or hydrochars) with reduced ash content [8].

Overall, slow pyrolysis is the preferred process for biochar production. The technology can be applied to almost all types of biomass feedstocks and the slow heating rates, coupled with low temperatures and long residence times, are appropriate for the formation of stable carbonaceous solid materials [9]. Moreover, it should be highlighted that for the above-mentioned processes, particularly pyrolysis, torrefaction, and HTC, there are other products of interest, such as bio-oil, which can be further processed into drop-in liquid biofuels; wood vinegar, which can be applied as a biopesticide; or HTC process water, which shows potential to be used in hydrothermal gasification for producing renewable gases or synthetic liquid biofuels. Addressing the application of these by-products is of extreme relevance to achieving circularity and, consequently, increased sustainability in biochar production.

Table 1 summarizes and compares the typical operating conditions and biochar yields of the described biochar production processes.

Table 1. Comparison of thermochemical processes for biochar production [2][6][7][9][10][11].

Process	Temperature (°C)	Residence Time (min)	Pressure (atm)	Other Conditions	Biochar Yield (%)
Slow pyrolysis	**300–800**	**>60**	**1**	**No oxygen; Moisture content < 15–20%; Heating rate < 10 °C/min**	**30–55**
Fast pyrolysis	**450–600**	**~0.02**	**1**	**No oxygen; Moisture content < 15–20%; Heating rate ≥ 200 °C/min**	**10–25**
Gasification	**750–1000**	**0.2–0.4**	**1–3**	**Limited oxygen supply Moisture content 10–20%; Heating rate ~1000 °C/min**	**14–25**
Torrefaction	**200–300**	**15–60**	**1**	**No oxygen; Moisture content < 10%; Heating rate < 50 °C/min**	**70–80**
HTC	**180–300**	**5–240**	**1–200**	**Moisture content 75–90%**	**50–80**

In line with the chosen production process, the physical-chemical properties of biochar are very important to define its final application. Biochar characteristics and yields are highly dependent on feedstock and operation parameters, particularly temperature. Ippolito et al. (2020) studied the influence of feedstock choice and process parameters on main biochar properties through a meta-analysis. The authors assessed that process type plays a minor role in biochar's physical-chemical properties, whereas temperature is the dominating parameter. Higher process temperatures can be responsible for increased carbon content and specific surface area (SSA) properties that promote soil improvement when using biochar. The authors also stated that feedstock choice has the largest influence on biochar properties, with wood-based feedstocks presenting higher SSA and crop- and grass-based biochars showing increased cation exchange capacities (CEC). The overall results of the study, including temperature and feedstock variations, are represented in **Table 2** [12].

Table 2. Basic biochar physicochemical and morphological properties (expressed on a dry basis) [12].

Property	SSA (m^2g^{-1})	CEC ($cmol\ kg^{-1}$)	AEC ($cmol\ kg^{-1}$)	CCE (%)	PV ($m^3\ t^{-1}$)	APS (nm)	Ash (%)	pH	EC ($dS\ m^{-1}$)
Pyrolysis type									
Slow	**183**	**44.9**	**4.90**	**6.10**	**2.04**	**52.3**	**19.2**	**8.7**	**4.45**
Fast	**98.6**	**48.1**	**5.33**	**11.2**	**3.66**	**1190**	**22.0**	**8.7**	**5.85**
Feedstock									
Wood-based	**184**	**23.9**	**5.65**	**9.04**	**7.01**	**74.6**	**10.2**	**8.3**	**6.20**
Crop wastes	**98.2**	**56.3**	**4.51**	**6.12**	**2.05**	**2320**	**21.1**	**8.9**	**5.72**
Other grasses	**63.4**	**63.3**	**5.05**	**n.d.**	**3.36**	**268**	**18.0**	**8.9**	**5.20**
Manures/biosolids	**52.2**	**66.1**	**7.77**	**14.2**	**0.82**	**27.3**	**44.6**	**8.9**	**3.98**
Process temperature (°C)									

Property	SSA (m^2g^{-1})	CEC (cmol kg^{-1})	AEC (cmol kg^{-1})	CCE (%)	PV (m^3 t^{-1})	APS (nm)	Ash (%)	pH	EC (dS m^{-1})
<300	27.1	44.4	n.d.	7.16	0.06	8.16	12.3	6.0	3.60
300–399	57.2	52.8	3.65	9.17	3.45	2340	17.8	7.8	5.72
400–499	108	35.0	n.d.	9.08	1.18	78.0	19.0	8.5	2.77
500–599	97.2	56.4	3.38	10.1	4.68	1140	23.2	9.0	8.05
600–699	178	33.7	n.d.	9.50	1.77	2000	23.5	9.5	4.85
700–799	204	53.0	5.27	12.9	8.87	9.19	26.6	10.0	4.29
>800	208	85.3	8.83	19.6	0.09	8.45	28.5	9.9	6.44

Note: Biochar properties considered for pyrolysis type and process temperature correspond to average values of all biochars analyzed in the study. SSA—Specific Surface Area; CEC—Cation Exchange Capacity; AEC—Anion Exchange Capacity; CCE—Calcium Carbonate Equivalent; PV—Pore Volume; APS—Average particle Size; EC—Electrical Conductivity.

As seen in **Table 2**, different feedstocks show different properties that affect biochar mass and energy yields and their designated applications [1][13]. Feedstocks rich in nutrients, such as manures and biosolids, produce biochar with high nutrient content, which is reflected in their values of CEC, AEC, CCE, and ash content. Moreover, wood-based biochar presents increased values of SSA and PV, meaning that these biochars have very significant potential for the removal of organic pollutants, carbon sequestration, and amending soil pH [14]. The pore size may vary between 2–18 nm (mesopore range) when the biochar is obtained from the pyrolysis of rice straw and tends to decrease with the process temperature [15]. Regarding biochar yields and feedstock variability and composition, in general, higher biochar yields can be obtained from feedstocks with higher ash contents, but the effect is less pronounced for ash contents >5% [16]. According to different studies, cellulose and hemicelluloses are the most promising components in producing volatile products via thermochemical conversion (e.g., pyrolysis) because these two compounds have a lower molecular weight than lignin and are easily released as pyrolytic gas. On the other hand, lignin is the main component responsible for biochar production due to its resistance to thermal degradation; as such, feedstocks with higher lignin contents generally lead to higher biochar yields [13][14].

Temperature is considered the most important parameter in controlling carbonization reaction mechanisms. This property influences the characteristics and yield of biochar to a greater extent when compared with residence time, heating rate, or feedstock particle size [1]. In general, process temperature affects SSA, pH, carbon content, stability, volatile fraction, and other biochar physical-chemical properties. Biochar produced at low temperatures can present high acidity, polarity, and low aromatic content, as well as low hydrophobicity. When process temperature is increased, acid functional groups (e.g., hydroxyl or carboxyl) and mass yields are reduced, meaning that alkaline functional groups increase along with pH and ash content. In addition, as a consequence of higher process temperature, volatile compounds are further released, resulting in larger SSA values and a more developed pore structure (increased PV) [2]. These features of high-temperature biochars indicate that their most suitable applications are related to the sorption or retention of nutrients and contaminants (organic and inorganic), while PV is assumed to affect water availability and soil aeration. Some authors have been emphasizing that biochar particle size can affect plant nutrient content, nutrient availability in growing media or soils, and PAH content [17][18][19]. The addition of biochar particles of different sizes can directly affect biochar-soil interactions, causing changes in the soil's physical properties. The smaller the biochar particles, the better the mixing and interaction with soil particles [20]. Given that biochar's characteristics are influenced by several parameters, the corresponding biochar properties also vary widely. This fact relates to arguably the most prominent aspect of biochar as a marketable product: the ability to be "tailor-made". Since biochar is becoming increasingly used in several areas, standardization before its final use is extremely important to generalize and predict its performance in different applications.

2. Biochar Applications

In the following subchapters, a description of potential biochar applications and related studies is presented to provide an idea regarding market diversity for these materials.

2.1. Agricultural Applications

Several studies have reported that the use of biochar for soil amendment improves soil physical properties, hydrological characteristics, water content, and water use efficiency, as well as soil fertility and crop yields [21]. Mixing biochar with decomposed manures, composts, and crop residues also improves nutrient use efficiency.

Soil application methods are heavily influenced by farming system type, labor availability, and power machinery available [22]. In Portugal, soils have very little carbon content. Thus, "tailor-made" biochars can be developed for particular soils and crops to achieve specific outcomes [23]. Despite these benefits, the feasibility of using biomass wastes to produce biochar for subsequent use in agriculture depends on its environmental and economic performance. Limitations exist since farmers are often risk-averse and have less investment capacity than other potential users, and there is still an enormous variability in the predictability of biochar impacts [24][25]. Agricultural biochar markets are also very seasonal, requiring producers to store large quantities of biochar or find alternative markets. The European biochar market has been mostly focused on livestock, with 90% of the biochar produced being used in livestock farming, whether mixed with feed, added to litter, or used in the treatment of slurries. This situation may be mainly due to the lack of regulation regarding the application of biochar as a soil amendment [26]. Therefore, in terms of marketability, it is important to understand which benefits matter the most to each farmer and which specific product biochar can potentially replace. Furthermore, the cost of biochar is critical for determining livestock pricing [27]. Some published cases of biochar use in agriculture are summarized in **Table 3**.

Table 3. Summary of studies about biochar applications in agriculture and livestock farming.

Biochar Use	Application Conditions	Obtained Results	References
Soil amendment	**Grapevine pruning biochar was applied to vineyard clay soils**	• ▪ Available water content increased by 23%	**Marshall et al. (2019) [28]**
	Biochar was applied to sandy loam soils at 5% (*w*/*w*) and 12.6 dS m^{-1} salinity rate	• ▪ Sorghum dry matter yield increased by 27.71% • ▪ Biochar alleviated the harmful impact of salinity	**Ibrahim et al. (2020) [29]**
	Eucalyptus wood waste biochar (550 °C) applied to different soils of mixture grassland (10 t ha^{-1})	• ▪ Improved legume production and competitiveness over grasses in mixed pastures • ▪ Increase in the amount of N fixed	**Mia et al. (2018) [30]**
	The addition of biochar to soils promoted an increase in crop yields	• ▪ Liming effect • ▪ Improved water holding capacity of the soil • ▪ Improved nutrient availability of crops • ▪ Around 77% of the studies found that < 50% (by vol.) of biochar addition in container substrates promoted plant growth, in particular, herbaceous plants	**Jeffery et al. (2011) [31] Huang and Gu (2019) [32]**

Biochar Use	Application Conditions	Obtained Results	References
Composting additive	Biochar was applied at a 10% rate (wt.%)	• ▪ Biochar at 10–30% rates succeeded in mitigating NH_3, N_2O, and CH_4 emissions • ▪ Biochar decreased the bioavailability of Cu and Zn in compost	Sanchez-Monedero et al. (2017) [33]
	Woody biochar (550 °C) was applied at a 10% rate (wt.%) to a mixture of slaughter waste, swine slurry, and sawdust compost	• ▪ Reduction of ammonia volatilization by 26–59% • ▪ Increase in nitrate (NO^{-3}) accumulation by 6.7–7.9 fold • ▪ Enhanced macro- and micro-nutrient content	Febrisiantosa et al. (2018) [34]

Biochar Use	Application Conditions	Obtained Results	References
Peat substitute & Growing medium	Biochar as a peat substitute	▪ Biochar can replace peat (≤ 70 vol.%) in soil-free substrates (no pH adjustment) without negative impacts on marigold biomass or flowering.	A.J. Margenot (2018) [35]
		▪ Incorporation of 50% (by vol.) biochar with peat increased container capacity, due to increased micropores, compared to those with 100% peat substrate.	Méndez et al. (2015) [36]
		▪ Incorporation of 20% or 35% (*w*/*w*) biochar with compost made from green waste increased container capacity.	Zhang et al. (2014) [37]
		▪ Incorporation of 60% and 70%, by vol. of the mixed hardwood biochar could substitute peat-based substrate in containers to grow plants.	Huang et al. (2019) [38]
	Mixtures of Biochar (at 0, 20, and 35%), humic acid (at 0, 0.5, and 0.7%), and composted green waste	▪ The highest quality medium and best growth were achieved with 20% biochar and 0.7% humic acid. ▪ Improved the particle-size distribution. ▪ Adjusted the bulk density (BD), porosity, and water-holding capacity (WHC) into ideal ranges. ▪ Decreased pH and electrical conductivity (EC). ▪ Increased macro- and micro-nutrient contents and microbial biomass C and N of the growth media.	Zhang et al. (2014) [37]
	Rice husk biochar mixed with perlite (1:1) as hydroponics growing medium	▪ 2 fold increase in shoot length, number of leaves, and fresh/dry masses of leafy vegetable plants ▪ Increase of 1.2 to 3.5 fold in leaf K, Mg, Mn, and Zn contents in most vegetable plants ▪ Decreased algal growth in the nutrient solution	Awad et al. (2017) [39]
Bedding litter	Addition of biochar at 10 to 20 wt.% to pine shavings for poultry bedding	▪ Increased water holding capacity by 21.6 and 32.2%	Linhoss et al. (2019) [40]

Biochar Use	Application Conditions	Obtained Results	References
Feed Additive	**<1% of daily rice husk biochar diet to ruminants, goats, and pigs; 2–6% of daily woody biochar feed to ducks and poultry**	• ▪ Increased weight gain, digestibility, N retention; increased egg weight • ▪ Lowered feed conversion ratio and enteric CH_4 emissions; decreased pathogens	**Man et al. (2021)** [26]
Heavy metal immobilization	**Biochar was applied (up to 10% rate) to heavy metal-contaminated soils.**	• ▪ Effective heavy metal (Cd, Pb, and Zn) immobilization • ▪ Decreased metal uptake in lettuce	**Kim et al. (2015)** [41]
Soil reclamation	**Wheat straw biochar and NPK added for sandy soil reclamation**	• ▪ Improved soil physical and chemical properties. • ▪ Increased total organic carbon content • ▪ Increased volumetric water content • ▪ Increased sandy substrate fertility • ▪ Achieved conditions for revegetation	**Bednick et al. (2020)** [42]

2.2. Control of GHG Emissions

Currently, 60% of the global warming effect is caused by CO_2 emissions, meaning that new strategies must be implemented to control carbon dioxide levels in the atmosphere. Biochar has an interesting ability to retain significant amounts of carbon for longer periods that may range from decades to thousands of years. In particular, biochar can be used for carbon sequestration by retaining CO_2 captured by the vegetable feedstock used for its production. When applied as a soil amendment, biochar contributes to climate change mitigation by fixing carbon in stable aromatic bonds that are resistant to microbial degradation. This stability reduces immediate labile carbon release into the atmosphere. Moreover, other GHG emissions such as N_2O and CH_4 are significantly minimized, depending on soil type, with reductions that may achieve more than 50%, considering the introduction of biochar amounts equivalent to 10% of soil mass and 20 t ha^{-1}. Conversion of animal or vegetable feedstocks into biochars also minimizes GHG emissions through the natural decomposition of such feedstocks [3][43][44].

A different carbon sequestration method involves the use of biochars to adsorb the CO_2 contained in industrial flue gases as a replacement for other high-cost materials (e.g., zeolites, porous polymers, and metal oxides). This process takes advantage of the good properties of biochar in terms of porosity and surface area (0.4–0.9 cm^3 g^{-1} and 1000–2000 m^2 g^{-1}, respectively), but requires a chemical activation post-treatment using KOH or sodium amide. Activated biochars produced from biomass feedstocks like hazelnuts, garlic peels, and olive oil wastes have shown adequate properties to adsorb CO_2, with retention efficiencies between 3.5–6.2 mmol g^{-1}. As an alternative, flue gases may be conducted through a bed of biochar heated at high temperatures and in the absence of oxygen to convert CO_2 into CO that may be employed for subsequent energy applications [3][45]. **Table 4** presents studies focused on possible biochar uses for GHG mitigation.

Table 4. Summary of studies about biochar applications for GHG emissions abatement.

Biochar Use	Application Conditions	Relevant Results	Reference
CO_2-capture	• ▪ Biochar was obtained from pyrolysis of olive stones and almond shells, followed by CO_2 activation. • ▪ The capture experiment consisted of the gas passage (with N_2 + CO_2) through a fixed-bed adsorption unit with biochar (25 °C and 100 °C, 1 atm).	**CO_2 adsorption performance was better for biochar from olive stones at 25 °C (3 mmol g^{-1}). Good regeneration capabilities were found for both biochars.**	**González et al. (2013) [46]**
CO_2-capture	• ▪ Biochar was prepared from hydrothermal carbonization of *Jujun* grass and *Camellia japonica*, and KOH/N_2 activation. • ▪ Tests were conducted in a gravimetric analyser (25 °C, 0.15–20 bar).	**Adsorption results were similar for both feedstocks and ranged between 3–21 mmol g^{-1}, with the highest results achieved when the pressure increased.**	**Coromina et al. (2015) [47]**
GHG mitigation	• ▪ Biochar preparation: pyrolysis of hardwood trees. • ▪ Introduction of 49 t ha^{-1} of biochar for cultivation tests using *Miscanthus* crops, for 2 years.	**Soils amended with biochar presented a reduction of CO_2 emissions of 33% and a global reduction of GHGs (CO_2, N_2O, and CH_4) of 37%.**	**Case et al. (2014) [48]**
	• ▪ Biochar preparation: gasification of hardwood and softwood chips. • ▪ Biochar was applied at a rate of 9.3 t ha^{-1} in field tests for the cultivation of corn and different types of grasses, during 148 days.	**No significant variations in CO_2 emissions were observed for all crop types, but N_2O emissions were suppressed by 27% with corn crops.**	**Fidel et al. (2019) [49]**

Although the use of biochar has demonstrated promising results for CO_2 capture contained in flue gases and GHG mitigation when applied to agricultural soils, results are strongly dependent on operational or application conditions. According to these studies, parameters like temperature and pressure significantly influenced CO_2-capture processes, while crop type and cultivation period affected GHG production during crop cultivation. Therefore, optimal conditions must be defined through field tests before establishing the best biochar for market purposes and intended applications.

2.3. Wastewater Treatment

Biochars can be considered a new low-cost alternative to commercial activated carbon applied in water disinfection and wastewater remediation processes. Batch adsorption studies have shown that biochars have significant adsorption capacities for contaminants present in real wastewaters, which is justified by their macroporous surface structure. These materials are therefore capable of remediating complex wastewaters while avoiding premature pore-clogging. The lower cost and history of land application combined with the need to remove new pollutants (e.g., antibiotics) has led to an increased interest in exploring biochars for new remediation solutions [50].

Conventional remediation strategies include, for instance, reverse osmosis, chemical oxidation or reduction, and precipitation. The use of biochars to adsorb aqueous contaminants presents important advantages over the aforementioned treatments, namely lower costs and the minimization of secondary by-products (e.g., sludges) [3]. Furthermore, biochar’s surface characteristics may be enhanced through activation methods to reach a higher degree of porosity and density of functional groups, enabling their application in the removal of aqueous organic and inorganic pollutants. These activation processes can be categorized into physical or chemical activation, including ball milling, acid-base modification, clay mineral modification, or metal oxide modification [51]. Activation treatments can further develop biochar’s pore structure and allow the development of functional groups (e.g., -COOH, -OH, and -CHO) that promote the capture of cationic and anionic inorganic contaminants, as well as organic pollutants (e.g., phenolic compounds and pesticides). **Table 5** shows studies focused on biochar applications for wastewater treatment and general pollutant removal.

Table 5. List of studies focused on biochar applications for wastewater treatment.

Biochar Use	Application Conditions	Obtained Results	References
Wastewater treatment	Catalytic ozonation of refinery wastewater with activated biochar from petroleum waste sludge.	Removal efficiencies for the following contaminants: total organic carbon (53.5%), Ox (33.4%), NOx (58.2%), and OxS contaminants (12.5%).	Chen et al. (2019) [52]
Removal of heavy metals	Pb^{2+} removal from battery manufacturing wastewater using bagasse biochar.	Maximum removal efficiency of 12.7 mg g^{-1} (75.4%) of Pb^{2+} was reached.	Poonam and Kumar (2018) [53]
	Jazaurin, ficus, orange, and mango biochars were used as filter media to retain several heavy metals.	Biochars were more effective with particle sizes <0.1 cm and initial concentrations between 50–150 mg L^{-1}, generating 99% of removal efficiencies for Cu^{2+}, Cd^{2+}, Pb^{2+}, and Zn^{2+}.	Hefny et al. (2020) [54]
Removal of nitrogen and phosphorus	Dairy manure runoff batch sorption using biochars produced from biomass	Adsorption results of 20–43% of ammonium and 19–65% of phosphate were achieved within 24 h	Ghezzehei et al. (2014) [55]
	Phosphorous removal from treated municipal wastewater	Phosphorous was removed effectively with relatively fast kinetics (<8 h) and a good adsorption capacity (8.34 g kg^{-1})	Zheng et al. (2019) [56]
Removal of organic contaminants	Biochar was produced by thermal activation (600 °C) from anaerobically digested bagasse	Sulfamethoxazole and sulfapyridin were removed from aqueous solutions with maximum adsorption capacities of 54.38 mg g^{-1} and 8.60 mg g^{-1}, respectively	Yao et al. (2018) [57]
	Gliricidia sepium biochar was used in batch sorption studies to remove aqueous dyes	Biochars produced at higher temperatures presented better adsorption efficiencies	Wathukarage et al. (2017) [58]
Stormwater management	Use of sand and biochar filters	• ▪ Primarily removal of metals/metalloids and total suspended solids • ▪ Minimal land requirement • ▪ Limited nutrient removal • ▪ High operation costs to prevent clogging	Mohanty et al. (2018) [59]
	Use of biochar in enhanced bio infiltration/bioretention system	• ▪ Removal of a wide variety of pollutants • ▪ Demand for larger areas • ▪ High installation and maintenance costs	
Constructed wetlands	Biochar was prepared from cattail and introduced into constructed wetlands	Results showed an improvement in removal efficiencies of chemical oxygen demand, NH_4^+ and total nitrogen, and a reduction of N_2O emissions. Heavy metals such as As^{2+}, Zn^{2+}, and Cu^{2+} were retained with rates of 35.4–83.9%, 8.2–23.7%, and 0.3–0.9%, respectively	Guo et al. (2020) [60]
	Biochar derived from wood was placed in a horizontal subsurface flow constructed wetland	Nutrient uptake by plant roots, plant biomass growth, and nutrient removal from wastewater were all enhanced with the biochar system. A pH reduction induced by plants in filter media was observed	Kasak et al. (2018) [61]

This literature survey demonstrated the large spectrum of contaminants that may be removed with biochars, as well as the diversity of effluents that may be remediated considering different adsorption techniques. In fact, the adsorption performances obtained in most studies were considered sufficiently good even without any biochar activation of physical or chemical nature, which represents a significant advantage in terms of lower energy demands, investment, and byproduct generation during biochar preparation. Other benefits include plant biomass development when biochars are applied in constructed wetlands while performing wastewater remediation. These applications suggest that environmental remediation may be a promising strategy for biochar valorization in the near future with the emergence of new pollutants generated by households, rural activities, and industry.

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