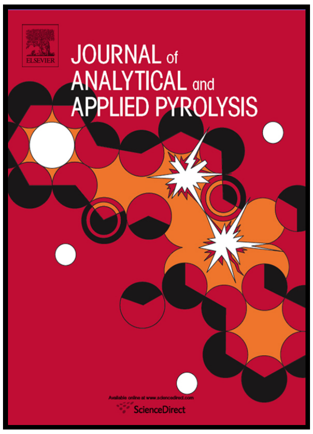

A critical review on production, modification and utilization of biochar

Yanqi Xie, Liang Wang, Hailong Li, Lena Johansson Westholm, Lara Carvalho, Eva Thorin, Zhixin Yu, Xinhai Yu, Øyvind Skreiberg

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How to select feedstock and production processes wisely for different applications of biochar

Yanqi Xie[1,2], Hailong Li[2*], Lena Johansson Westholm[2], Lara Carvalho[2], Liang Wang[3**], Eva Thorin[2], Zhixin Yu[4], Xinhai Yu[5], Øyvind Skreiberg[3]

1 Tianjin Key Laboratory of Refrigeration Technology, Tianjin University of Commerce, Tianjin, China

2 School of Business, Society & Engineering, Mälardalen University, Vasteras, Sweden

3 SINTEF Energy Research, P.O. Box 4761, Sluppen, 7465 Trondheim, Norway

4 Department of Energy and Petroleum Engineering, University of Stavanger, 4036 Stavanger, Norway

5 Key Laboratory of Pressure Systems and Safety, Ministry of Education, School of

Mechanical and Power Engineering, East China University of Science and Technology, Shanghai, China

* corresponding author: hailong.li@mdh.se; lihailong@gmail.com, School of Business, Society & Engineering, Mälardalen University, Vasteras, Sweden

** corresponding author: liang.wang@sintef.no, SINTEF Energy Research, P.O. Box 4761, Sluppen, 7465 Trondheim, Norway

Abstract

There has been an increased interest in the production of sustainable biochar in the past years, as biochar show versatile physicochemical properties and therefore can have a wide applicability in diverse fields. Comprehensive studies have been made to characterize biochar produced from various biomass materials, usingdifferent production technologies and under different process conditions. However, research is still lacking in correlating biochar properties needed for certain applications with (i) selection of feedstock, (ii) biochar production process and conditions and (iii) biochar upgrading and modification strategies. To produce biochar with the desired properties, there is a need to establish and clarify such correlations, which can be used for further proper selection of feedstock, tuning and optimization of the production process and more efficient utilization of biochar. On the other hand, further elucidation of these correlations is also important for biochar-stakeholder and end-users for predicting physiochemical properties of biochar from certain feedstock and production conditions, assessing potential effects of biochar utilization and clearly address needs towards biochar critical properties. This review summarizes a wide range of literature published on the impact of feedstocks and production processes and reactions conditions on the biochar properties. In addition, this review reports and discusses the most important biochar properties required for the different potential applications. Based on this review, knowledge gaps and perspectives for future research have been identified regarding the characterization and production of biochar. This review has also highlighted the importance of assessing performance of biochar for certain applications.

Keywords: Biochar; properties; feedstock; applications; production

Highlights:

- Feedstock, production process and conditions and modifications, influence specific biochar properties to a different degree.
- Requirements on the properties of biochar for different applications have been identified and summarized.
- The correlation between biochar properties and requirements of different applications have been reviewed.
- Recommendations are given regarding selection and improving production processes and feedstock for producing biochar designed towards certain applications.

Nomenclature

Abbreviations

AD	Anaerobic digestion	AW	Animal and human waste
BF	Blast furnace	BS	Biosolids sludge
C	Carbon	CEC	Cation exchange capacity
DOC	Dissolved organic carbon	FC	Fixed carbon
FAME	Fatty acid methyl ester	HB	Herbaceous biomass
H/C	Hydrogen-to-carbon ratio	HHV	Higher heating value
HMs	Heavy metals	HOCs	hydrophobic organic contaminants
HTT	Highest treatment temperature	O/C	Oxygen-to-carbon ratio
OCs	Organic compounds	PC	Pulverized coals
SSA	Specific surface area	TOC	Total organic carbon
VM	Volatile matter	WD	Woody biomass

Symbols

Ca	Calcium	CO_2	Carbon dioxide
H_2O	Water	H_2S	Hydrogen sulfide
K	Potassium	Mg	Magnesium
Na	Sodium	N	Nitrogen
$-NH_2$	Amine Symbols	NH_3	Ammonia
NH_4+	Ammonium ion	-OH	Hydroxyl
P	Phosphorus	SO_2	Sulfur dioxide
W_f	Dry mass of the produced biochar	W_0	Dry mass of the precursors
ρ_e	Envelope density	ρ_s	Skeletal density

1 Introduction

Biochar is a black, carbon-rich and porous solid material (similar to charcoal) that can be produced through thermochemical conversion of biomass with presence of little or no oxygen [1]. Biochar has unique chemical, physical and biological properties, which make it an interesting material with diverse applications and a promising solution to some global problems. In the past decades, there have been increasing interests, studies and practices in converting biomass into biochar, given its multifold benefits and diverse application potential [2]. Review articles on biochar have been published with general focuses on: (1) production of biochar, (2) properties of biochar, and (3) applications of biochar, as summarized in Table 1. Naturally, specific end-user applications have different requirements to the biochar properties; and the properties can be clearly affected by the (i) production technology and process conditions, (ii) the type of feedstock and (iii) post modifications. Nevertheless, there is a knowledge gap between how to select the feedstock and how to design the operating conditions aiming to produce biochar with properties that can meet and satisfy requirements of certain applications. The lack of knowledge has hindered the further development and application of biochar. This work reviewed a wide range of studies published on biomass feedstock, biochar production technology and conditions and needs of various applications on biochar characteristics. Further, the work gives recommendations appropriate to correlation and connecting details on production of biochar, desired biochar properties and proper application of biochar.

In this work, the selection of reviewed articles has followed a systematic protocol. Firstly, ~~with~~ considering the overall objectives of the current work, published review articles about biochar production and characterization, modifications and major applications, were searched and gathered. Keywords used for literature searching in *Google Scholar* and *Scopus* database, were "biochar property", "biochar application", "biochar production", and "property impacts". The recent advances and studies on the same topics and focus on biochar were surveyed for collecting data that can provide overarching changes in biochar physiochemical properties that can be compared with those required by different applications. Secondly, knowledge gaps were identified in orer to provide guidance for preparing biochar with the desired properties. Thirdly, the identified review articles provided a good database of reference articles relevant to the reviewed topics. Finally, a cross comparison was done between the surveyed reference articles and those included in the review articles to avoid missing important and the latest findings. The collected articles were further screened and categorized according to the research questions and the important information was retrieved and discussed.

In order to achieve the objective, the following research questions were defined:

- RQ1: What are the requirements on biochar properties from specific applications?
- RQ2: How are the biochar properties correlated with the production conditions and feedstock characteristics?
- RQ3: How should the production process and feedstock be selected to meet the requirements of different applications?

The following content is organized as follows: Section 2 briefly introduces the important properties of biochar; Section 3 summarizes the requirements of different applications on biochar properties; Section 4 critically discusses the influences of feedstock and processes on the biochar properties; Section 5 maps out the selection of feedstock and production processes for different applications; and Section 6 summarizes the key findings, identifies the knowledge gap and gives recommendations for further work.

Table 1 Summary of review works on biochar

Reference	Scope	Major findings
Review on properties of biochar		
[3]	Review on fundamentals of adsorption kinetics, mechanisms and equilibrium of biochar-based sorbents towards micropollutants.	Identification of a direct link between the biochar surface properties and its adsorption abilities. The authors highlight the need of incorporating mechanistic analysis in future research to select proper kinetic models.
[4]	Review on key properties of biochar and correlations of them with between influential factors, including pyrolysis temperature and different feedstock.	Temperature identified as the most dominant influence on all properties.
[5]	Review on the methods for assessing biochar-stability.	Classification of methods to assess the stability biochar as: I) analysis of biochar micro carbon structure, II) determination of biochar oxidation resistance, and III) evaluation of biochar persistence by modelling biochar incubation and mineralization rate.
[6]	Review on biochar properties produced at different temperatures and from different feedstock.	Quantitative approaches can potentially be used to predict and link the biochar production conditions with its performance in different applications. The limitations lay in the lack of comparable data to perform such studies.
[7]	Review on the production and advanced utilization of biochar via selective pyrolysis of lignocellulosic biomass	Properties of biochar are influenced by many operation parameters. Adjusting operation parameter together with in-situ activation and doping with heteroatom could be efficient measures to alter properties of biochar, especially the adsorption capacity and electrochemical performance. These measures should be synergistically conducted and optimized to produce high quality biochar economical and ecologically friendly.
[8]	Review on recent advances in biomass pyrolysis	Pyrolysis mechanisms of biomass and physicochemical properties biochar are considerably related to and affected by pyrolysis conditions, and organic and inorganic compositions of biomass. Interactions between pyrolysis of biomass components with heat and transfer in the pyrolysis process are also critical in terms of formation and properties of intermediate and final products. Co-pyrolysis and catalytic pyrolysis have great potential for producing high quality biochar and by-products from the biomass.
Review on production of biochar		
[9]	Review on the thermochemical processes for biomass conversion into biochar, including pyrolysis, carbonization and gasification.	Biochar yield and property are heavily affected by production conditions.
[10]	Review on production and applications of biochar in removing agricultural contaminants such as antibiotics, pesticides and toxic metals.	Biochar properties can be considerably improved by pre and post treatment methods via e.g., chemical or magnetic modifications of raw feedstock prior to pyrolysis. It is important to select the appropriate raw materials, optimizing production conditions to identify the lowest-cost fabrication methods.
[11]	Review on production of biochar from various lignocellulosic biomass precursors and the parameters influencing biochar properties. Recent advances in	High contents of lignin in lignocellulosic biomass favors the yield of biochar. Temperature, heating rate and residence time are found to have direct influences on the production and properties of biochar.

	modification of biochar to enhance biochar adsorption capacity were also reviewed.	Activation methods can enhance the specific surface area and functional groups distribution of biochar.
[12]	Review on the physicochemical properties and applications of biochar from gasification.	Yield of biochar from the gasification process is lower than torrefaction and slow pyrolysis. Biochar from gasification had different specific surface areas and total pore volumes compared to those from slow and fast pyrolysis. When using O_2 or steam as gasifying agent, the specific surface area could be twice of that from pyrolysis for the same feedstock.
[13]	Reviewed the biochar production through pyrolysis of biogenic wastes.	Biochar yield is considerably related to the biomass physicochemical properties, such as the content of moisture and the presence of cellulose or lignin. The product distribution and their quality strongly depend upon the process parameters, such as temperature, heating rate, residence time etc.
[14]	Review and comparison of processes for production of biochar from different biomass materials. Physical and chemical activation methods used to improve the physicochemical properties of biochar and their effects were also reviewed.	Properties of biochar are influenced by the type of raw biomass material and the conversion process, as well as the process parameters such as the rate of heating and residence time.
[15]	Review on the principles and concepts involved in biochar production, the factors affecting biochar quality and biochar applications.	The quantities and qualities of biochar are affected by the production conditions and properties of feedstock, which can be adapted corresponding to the requirement of applications. More work on producing biochar in large-scale is needed to assess the environmental and economic feasibility of the process.
[16]	Review on the production of biochar from various sources of lignocellulosic biomass and its application in agriculture and wastewater treatment processes.	Higher biochar yields often can be obtained from biomass feedstock with high lignin content. Production conditions including temperature, retention time and heating rate were identified as having strong impacts on yield and properties of produced biochar. Physical, chemical and biological modification methods can be applied to alter biochar properties including specific surface area and functional groups on biochar surface.
[17]	Review on the possible biochar modifications, functionalities, applications and regeneration.	Chemical modification methods can improve the surface properties of biochar. Oxygenated functional groups are generated with acidic modification while high ratios of surface aromaticity are produced with alkaline modifications. The removal of organic and inorganic contaminants can be enhanced with biochar impregnated with nano-scale materials.
[18]	Reviewed the impacts of different torrefaction parameters on the final improvement of the torrefied biomass qualities.	Torrefaction temperature affects properties of produced biochar more obviously than the other production process parameters. The residence time affects characteristics of biochar only in certain temperature ranges.
	Reviewed the mechanisms of chemical modification and explored their impacts on physicochemical properties, functionalities and applications of biochar.	Chemical modifications, including oxidation, amination, sulfonation and impregnation of metal oxides into biochar structures, can have major impacts on the biochar chemical bonds and functional groups.
[19]	Reviewed the property upgrading of some raw biomass through torrefaction pre-treatment.	Combustion efficiency of biomasses is enhanced after torrefaction treatment due to increased fixed carbon content and calorific value as well as by reducing the volatile content via torrefaction.
[20]	Review on the torrefaction of biomass materials	Torrefaction temperature and residence time are key parameters to affect yield and properties of torrefied biomass
[21]	Review on the different environmental applications of biochar composites and the important factors influencing its	Different agents for modifying biochar properties have been studied, including clays, metals, metal oxides, zero-valent ions and organic compounds. In

	characteristics. The factors influencing adsorption capacity of biochar and different adsorption mechanisms were discussed.	general, the modifying agents can considerably improve the adsorptive capacity of biochar.
[22]	Reviewed the methods for biochar modification and the corresponding mechanisms. The benefits of using modified biochar were also discussed for the management of contaminated soils and water.	Different methods to modifybiochar can result in different changes in the specific surface area, functional groups and pore volume. The importance of minimizing the effect of biochar modification methods to avoid environmental contamination was highlighted.
Review on applications of biochar		
[23]	Review on application of biochar in soil to sequester carbon and evaluated the corresponding benefits from the agronomic perspective.	Adding biochar in soil can generally enhances the growth of plants and nutrient content in soil, while decrease the emission of N_2O. Burying of biochar in soil is a promising large-scale strategy for CO_2 offsetting and carbon sequestration. More efforts are needed to find how to realize these benefits that can vary depending on the type of biochar and soil and the application rate.
[24]	Review on the recent findings about using biochar to remove heavy metals from aqueous solutions.	Adsorption mechanisms depend on biochar properties and target pollutants. Endothermic conditions can be beneficial for using biochar to remove heavy metal.
[25]	Review and assessment of the impacts of biochar on soil biota.	Impacts of biochar on soil fertility are mainly due to that biochar can increase the pH in acid soils or improve nutrient retention through cation adsorption; and the effects on harbouring plant communities are due to the sorption of allelopathic compounds as biochar has high specific surface areas and pore sizes.
[26]	Reviewed different ways to produce biochar using biomass and the impacts of adding biochar to agricultural soils on soil properties and fertility.	Increasing the peak pyrolysis temperature of can affect the properties of biochar, such as aromaticity, fixed carbon content and porosity. As introduced in soil, biochar can further enhance the stability of the carbon and nutrient retention in soil, which could also improve soil−water retention and soil aeration.
[27]	Assessed different interactions occurring between soil micro-, meso- and microorganisms and biochar stability.	Increasing pyrolysis temperature and extending residence time can decrease the rates of biochar mineralization. Release of CO_2 from soil upon biochar addition may come from (i) priming of native soil organic carbon pools, (ii) biodegradation of biochar components from direct or indirect stimulation of soil organisms or (iii) abiotic release of biochar.
[1]	Review on the recent applications of biochar in water and wastewater treatment.	Adsorption capacities of biochar for different contaminants are summarized. Main conclusions are: (i) biochar from bamboo was the best for removing methylene blue dye, (ii) biochar from cow manure, pig manure, peanut straw offered excellent adsorption capacity for Cu2+, (iii) biochar from cow manure showed the maximum capacity for removing lead in water. No single biochar was found that can remove all the contaminants from water.
[28]	Review on the application of biochar in water treatment plants to remove organic and microbial contamination from the perspectives of potential benefits and challenges.	Biochar can be used to remove organic (e.g., pesticides, dyes, pharmaceutical products) and microbial contaminants (e.g., E. coli) as well as replace or minimize the use of expensive sorbents. Releasing organic matter through leaching when biochar is produced at lower temperature (<550°C) has been pointed out as a problem. More research is needed to investigate the application of biochar in demonstration-scales.
[29]	Reviewed and summarized the state of knowledge regarding biochar interactions with soil in the long-run and highlighted the key concerns that require further	The review has shown that there are many benefits of applying biochar in soils. A deeper understanding of the effects of biochar on soil health is still required. In addition, it was remarked that the feedstock properties

	research.	and pyrolysis conditions need to be optimized to design biochar for specific uses. The authors also stated that long-term experiments are needed to understand the effect of aging on biochar.
[30]	Reviewed and summarized the sources and production of biochar, status in biochar removal of organic pollutants, adsorption mechanisms, relevant adsorption parameters and regeneration methods.	The removal mechanisms for different organic contaminants will vary with the surface chemistry of biochar. The adsorption mechanisms include electrostatic attraction, pore filling, interactions between π-π electron donor acceptors, H-bonding, complexes adsorption, hydrophobic interactions and partition uncarbonized fraction. Regeneration of biochar includes thermal regeneration, solvent regeneration, microwave radiation regeneration and supercritical fluid regeneration.
[31]	Review on the production technologies of biochar and their corresponding properties and recent progress in using biochar for the removal of heavy metals and organic pollutants.	The properties of biochar are mainly affected by the temperature and residence time of pyrolysis and feedstock. The removal of heavy metals and organic pollutants is mainly through single or combination of flowing mechanisms including electrostatic attraction, ion-exchange, physical adsorption and chemical bonding.
[32]	Review on using biochar as a green and versatile catalyst support for applications, such as synthesis of chemical, production of biodiesel from biomass, and degradation of pollutant in the environment in soil.	The active site accessibility for substrates, associated with the physicochemical characteristics of biochar, is identified as the key factor influencing performance of biochar as catalyst. Availability of catalytic sites on biochar surfaces can be enhanced through post modifications.
[33]	Review on utilization of biochar-based adsorbents and their capacity to remove contaminants in water as well as highlight prospects, constraints, risks and knowledge gaps on biochar use in water treatment.	Integration of biochar into the water-sanitation-nutrient-food nexus can benefit the public health. It can provide a low-cost adsorbent for water treatment and increase food security by using char as soil amendment and fertilizer.
[34]	Review on catalytic applications of biochar. It focused on the catalytic challenges and practices of biochar (e.g., biodiesel production, tar reduction in bio-oil and syngas, enhanced syngas production, etc.).	Since the morphology and surface functionality of biochar can finely tuned via various physical and/or chemical treatments, the authors concluded that biochar has a high potential to replace expensive and non-renewable conventional catalysts. Additionally, biochar was found to have potential as an inexpensive electrode of MFC systems.
[35]	Review on the role of biochar surface in different applications including pollutant interactions with surface functional groups and the impact of parameter change on biochar capacity to remove a certain pollutant.	The removal of contaminants is mainly due to interactions with active functional groups of biochar. Feedstock type and pyrolysis conditions were pointed out as the most important factors impacting the biochar´s removal processes but the adsorptive capacity for a specific pollutant can be improved by changing biochar-production conditions.
[36]	Reviewed the recent advances in biochar utilizations as catalysts and supercapacitors.	The high content of oxygenated functional groups and high specific surface areas enable biochar to be used as metal-free catalyst, which demonstrates favorable catalytic performance, but has relative low efficiency and low abrasive resistance. Considering the low cost and satisfactory performance, using biochar as electrode is also promising. However, a wide application needs to further improve the properties of biochar.
[37]	Review on the technologies for preparing biochar, the biochar properties and the implications biochar has on the physical and chemical properties of the soil.	The authors concluded that the main factors controlling the quality of biochar include biomass material, retention time and temperature. Returning biochar to the soil can improve soil compaction, porosity, permeability, soil density, water content and bulk density. Biochar also promotes mineralization, fixation and transformation of organic nitrogen in soils. Biochar can aid in microbe growth and propagation. Biochar can be used in polluted soils to absorb poisonous and pernicious substances. In

		addition, biochar can retain the carbon in the soil and reduce the emissions of CH_4, N_2O nand CO_2.
[38]	Review on the applications of biochar for contaminant management in soil and water.	Several variables are involved in determining the exact role of biochar for the removal of different contaminants, e.g., pyrolysis conditions and feedstock type. Application of biochar to remediate contaminated soils can provide additional benefits in terms carbon sequestration.
[39]	Reviewed the characteristics of biochar and its applications in anaerobic digestion	Biochar promotes the biomethane production, by acting as support for bacteria colonies, conductor for electron transfer among species, sorbent for indirect inhibitors, and reactant in biochar labile carbon methanization.
[40]	Comparison of characteristics of biochar derived from wastewater sludge to more conventional biochar and reviewed the possible applications of wastewater biochar.	Sludge biochar has a lower C content and higher H/C rations when compared with other biomass derived biochar. Sludge biochar can be used as adsorbent in particular to recover nutrients or remove metals and antibiotics from wastewaters. The biochar also shows a good performance in amending soils and do not pose threats to the environment when applied in agricultural lands.
[39]	Reviewed the role of biochar in anaerobic digestion processes.	Utilization of biochar has been identified as an effective measure to increase anaerobic digestion processes and performance, which can improve global conversion efficiency of biomass with economic benefits. Biochar may promote biomethane production by acting as a support for bacteria colonies, as conductor for electron transfer, as sorbent for indirect inhibitors and as reactant in methanization.
[41]	Review on impacts of pyrolysis temperature and characteristics of feedstock on biochar properties and its application in soil.	Physio-chemical properties of biochar are correlated to the temperature of pyrolysis for each feedstock group. Specific surface area, porosity and pH are identified as critical properties for the ability of biochar to hold moisture and retain fertilizer nutrients, which can further improve nutrient utilization efficiency.
[6]	Review on the mechanisms controlling the presence of contaminants in water and their removal by biochar.	Based on surveyed qualitative analyses and adsorption data, biochar can be efficiently used as adsorbent for cleaning contaminants in water. Using low-cost and abundant waste biomasses for biochar production can be an efficient way for waste management.
[42]	Review on the biochar properties relevant to simultaneously promote anaerobic digestion stability as well as increase biomethane yield and the quality of the digestate.	Critical biochar properties that can promote anaerobic digestion were identified, including alkalinity, surface morphology, surface chemistry and microstructure. Addition of biochar affect anaerobic digestion to different extents.
[43]	Review on using biochar application to improve anaerobic digestion from the perspectives of biogas production, methane content, buffering capacity, and alleviation of ammonia and VFAs inhibition.	When the concentrations of ammonia nitrogen are high, adding biochar can improve the tolerance of anaerobic digestion system. Biochar can improve the efficiency of anaerobic digestion, as it can reduce the inhibition of ammonium due to its high specific surface areas and functional groups, which can increase its ammonia adsorption rate.
[44]	Review on the modification methods (generally chemical methods) for biochar properties, the corresponding heavy metals (HMs) removal mechanisms and the potential for reutilization of biochar loaded with HMs.	Surface reduction modifications is a better method to improve the content of basic functional groups, especially nitrogenous functional groups which is a reactive functional group that efficiently complexes with HMs, with high stability constants reported for the formed complexes.

[45]	Review on use of biochar to improve soil quality, and for carbon sequestration and enhancement of crop yield. A meta-analysis of the data was performed based on multivariate statistical analysis.	Introduction of biochar in soils can increase the crop yield. The greater nutrients available in the soil can be accomplished with biochar produced at lower temperatures. The original properties of the soil are also an important factor that effects role of biochar as soil amendment agent.
[46]	Review on the research on biochar and its use in crop agriculture and livestock production.	The authors concluded that biochar has the potential to be utilized as animal nutrition (feed additive to improve e.g., digestion, feed conversion ratio) as well as odor and gaseous emissions mitigation.
[47]	Discussed the suitability of biochar in various electrochemical applications related to energy storage and conversion.	It has been concluded that biochar is a potent material of interest for electrochemical energy storage and conversion. It also pointed out that the conversion efficiency and quality of biomass into biochar are required to be maintained without additional steps for treatments and it is necessary to reduce the impurity contents to acceptable minimum.
[48]	Reviewed the use of biochar in composting, considering both the effects on adding biochar in the composting process, the influence on the product and its application as organic fertilizer.	Biochar can play active role during composting process, including increasing water holding capacity, decreasing emissions of NH_3, H_2S, CH_4 and N_2O emissions, and positive effect on the microbial activity. The positive effects of biochar on the composting product and its use as organic fertilizer or soil amendment includes making the product less toxic, enhanced physicochemical properties and increased fertilising effect leading to higher crop yields.

2. Requirements on biochar properties for different applications

2.1 Characteristics of biochar

Biochar applications range from soil amendment [49], carbon sequestration [50] and adsorbing metals and nutrients from waters and wastewaters [41,51]. Additionally, biochar can also be used for heat generation, metal production, flue gas cleaning and in the production of functional materials [4]. Biochar with certain properties is desired to meet and satisfy specific requirements of each application to optimize its effectiveness [1]. The properties of biochars can be described in terms of yield as well as a number of physical and chemical properties. These properties are briefly defined in Table 2. A short explanation on the relevance of each biochar property is also included.

Table 2 Summary of biochar properties

Properties	Definition	Indication
Yield	The ratio of pyrolyzed product mass to raw biomass mass	Indication of biochar production efficiency
Density	Mass of the material divided by the volume occupied that includes interstitial space	Low density and high porosity indicate low weight per unit volume. Bulk density is important for shipping and handling of biochar.
Specific surface area (SSA)	Total surface area of a material per unit of mass.	High SSA indicates greater adsorption capacity and water holding capacity of biochar
Porosity	Ratio of the volumes of voids or pore space divided by the total	The pore volume, pore size distribution pore structure affects the ability of biochar as

	volumen	adsorbent, soil amenbdant and reactivity under certain conditions
Electric conductivity	How much voltage is required to get an amount of electric current to flow	It represents the ability of a material to conduct electric current
Elemental composition	Content of element C, H, N, and S	Indicator of the degree of carbonization, stability and amorphous carbon structure
	H/C mole ratio, O/C mole ratio	Low O/C and H/C mole ratio normally indicates high stability of biochar
pH-value	$\mathrm{pH} = -\log[H^+]$	Alkalinity (or acidity) of biochar (c)
Surface functional groups	Aromatic and heterocyclic carbons on biochar surfaces	Indicator of biochar's capacity to adsorb pollutants and contaminants in aqueous solution, activity of biochar in AD, performance of biochar as catalysis
Heating value/energy content	Heat generated per unit mass or per unit volume	Indicator of the upper limit of the available thermal energy produced by a complete combustion
Fixed carbon content	$\mathrm{FC}(\%) = [100 - (\mathrm{VM} + \mathrm{Ash})]$ Content of fixed carbon after substracting ther percentages of moisture, volatile matter and ash from one biochar sample	Indicating carbonization degree of one sample and content of carbon of the sample
Volatile matter content (VM)	Weight loss after heating the biochar to 950℃ and holding for 7 min	VM and FC reflect the labile and recalcitrant fractions of biochar
Ash content and composition	non-combustible residues from from the inorganic or mineral components of biochar	Ash content associated with alkaline chemical species su is often related to liming effects of biochar. The contents of certain inorganic elements (i.e., Ca and K) in biochar are important for potential agronomic and environmental bebefits for fertilizing soil and enhancing soil quality
Cation exchange capacity	Amount of exchangeable cations that biochar is able to hold	Indicator of biochar's impacts on soil fertility
Hydrophobicity and water holding capacity	Affinity of biochar to water and capacity of biochar to contain and retain water	Indicator of biochar's ability to retain water in the soil, decrease mobility of the water and reduce water stress in plants

2.2 Key properties needed by different applications

The properties required by different applications of biochar collected from the literature and the key properties are presented in Table 3.

Table 3 Applications are mainly related to the properties of biochar

Applications	**Purpose**	**Key properties of biochar**	**Requirements**
Wastewater treatment	Removal of heavy metal	pH, surface functional groups	High pH in acid environment and oxygen-containing functional group are preferred
	Removal of nutrients	surface functional groups, SSA	Oxygen-, acidic, phenolic and carboxyl groups on surface are

			preferred
	Removal of organic contaminants	SSA, pH, H/C ratio	Low pH, high SSA and low H/C ratio are preferred
Soil amendment	Improve fertilizer use efficiency or nutrient use efficiency	pH	High pH is preferred
		SSA and porosity	Large SSA and porosity are preferred
	Soil carbon sequestration	Yield and carbon content	High yield of biochar and carbon content are preferred
	Soil conditioner	SSA, porosity and nutrient content	Large SSA and porosity are preferred
Biogas production	Biochar as buffer	pH	High pH is preferred
	Biochar as syntrophic partners for biogas production	Potassium (K) of biochar and trace elements	High concentrations of potassium are preferred
Composting	Biochar as buffer	pH	High pH is preferred
	Increasing aeration	SSA	Large SSA is preferred
	Adsorption of NH_3, NH_4^+	SSA, pore volume, surface functional groups	Large SSA and acidic functional groups are preferred
	Affinity of heavy metals	SSA, surface functional groups	Large SSA and acidic functional groups are preferred
	Retention of nutrients	SSA and CEC	Large SSA giving a high CEC
	Protective habitat for microorganisms	pore volume	Macro-pores with a size comparable to bacteria
Gas cleaning	NOx removal H_2S removal	SSA, pore volume	Large SSA is preferred
Catalyst	Catalyst in a variety of chemical processes	SSA, porosity	Large SSA and porosity is preferred
		Surface functional group	Large SSA and more SO_3H group are preferred
Metal production	Biochar as reductant	VM	Normally biochar with low VM is requested
		FC	HighFC values are preferred
		SSA and pore volume	Low SSA and pore volume are preferred
	Biochar as fuel	HHV	A high HHV value is preferred
Electrochemical applications	As electrocatalyst	SSA and porosity	High SSA and porosity are preferred
	As electrodes of MFC	SSA, carbon and ash contents	High SSA and carbon content and low ash content are preferred
	As electrodes of supercapacitors	SSA, pores distribution, wettability, electric conductivity	High SSA (>2000 m^2/g), low wettability and high electric conductivity are preferred
	As electrodes of batteries	SSA, pore distribution, N content	High SSA and N content are preferred

2.2.1 Wastewater treatment

Biochar can be used to remove different pollutants in wastewaters including heavy metals, nutrients and organic compounds. Micropollutants which have negative impacts in wastewaters can also be adsorbed by biochar [52], but there is currently little research on this aspect.

Table A1 in Appendix A presents key studies on the use of biochar to remove contaminants from aqueous solutions where the needed biovhar properties were highlighted.

2.2.1.1 Removal of heavy metals in wastewater

Heavy metals are non-biodegradable and can pose a significant risk to the public health and to the environment as they are toxic and carcinogenic at higher concentrations [53]. Biochar shows a great affinity to heavy metals and many studies have been conducted to investigate its ability to remove metals in aqueous solutions [1,35,54]. Li et al. [55] have identified specific surface area, porosity, pH, surface charge, functional groups and mineral composition of biochar as important properties that can play a role in heavy metal adsorption. Heavy metals can be physically adsorbed onto the surfaces of biochars, and removal of heavy metals is mainly via surface interactions through ion-exchange and complexation between biochar functional groups and heavy metal ions. Oliveira et al. [35] reported that the pH and surface functional groups are two critical factors influencing heavy metal surface interactions with biochar . Samsuri et al. [56] stated that the biochar´s pH was more important than other properties regarding adsorption of Zn, Cu and Pb. The adsorption of metal on biochar is also influenced by the solution pH, as it affects the surface charge of the adsorbent as well as the degree of ionization and speciation of the metal ions in solution [20]. An acidic environment is favorable as using biochar as asorbent, and the adsorption efficiency can be enhanced by increasing pH of solution. It is important to distinguish between the pH of biochar and the pH of the solution. The pH of the biochar is an inherent property of the material that mainly depends on the amount of organic functional groups, soluble organic compounds, and inorganic alkali salts . Whereas the pH of the solution corresponds to the amount of hydrogen ions in the solution (wastewater in this case). The pH of the solution can be adjusted by adding an acid or basic substance. The pH of the solution is adjusted to optimize the adsorption mechanisms as it can influence the charge of the specific surface area and the degree of ionization of the adsorbent [57]. Premarathna et al. [21] investigated biochar produced by pyrolysis of hard wood at 450°C and corn straw at 600°C to remove Cu^{2+} and Zn^{2+}. The results showed that the adsorption capacity increased with increasing pH until a pH value reached 5. Similarly, Tursi [22] and Sohi et al. [23] verified an increase in Cu^{2+} removal with increasing pH up to a value of approximately 7. Similar trends were obtained for Cd^{2+} adsorption by Inyang et al. [58] and Lehmann et al. [25], which was increased with increasing pH up to a pH value of 5-8. The low metal adsorption efficiency at low pH values can be explained by the high concentration of H^+ ions that inhibits the contact between the heavy metals and biochar. As the pH increases, the concentration of H^+ ions in the solution decreases, and the metal adsorption capacity is therefore increased due to the negative charge of functional groups such as carboxyl and hydroxyl groups on the biochar surface [26]. However, with further increase of the pH, the sorption capacity of biochar decreases as the metal ions start to hydrolyze and metal precipitation occurs [27].

The functional groups on biochar surfaces can also affect the adsorption capacity of heavy metal [1]. Studies indicated that biochar´s surface functional groups, mainly oxygen containing groups such as carboxylate and hydroxyl, can have either electrostatic attractions, ion-exchange or surface complexation interactions with heavy metals [28]. A multivariate analysis carried out by Lone et al. [29] indicated that functional groups on the biochar surface are important regarding providing sites for binding heavy metals, such as Cd^{2+} and Pb^{2+}. In general, the more oxygen-containing functional groups of biochar, the better adsorption effect of heavy metals.

2.2.1.2 Removal of nutrients in wastewater

Nutrients including nitrogen (N) and phosphorus (P) can be hazardous to the aquatic environment if their concentrations in water bodies are too high. Nutrients can be removed from domestic wastewater by using biochar under different conditions [59–62]. Huggins et al. [63] investigated nutrient removal from industrial wastewater (brewery water) while Gupta et al. [64] and Zhou et al. [65] reported on nutrient removal from synthetic wastewaters.

Removal of P in the wastewater by biochar can be realized through different mechanisms that often associated with properties of biochar. Physical and chemical properties of biochar are of importance for the removal of P and several removal mechanisms can be involved, including among these precipitation with Mg^{2+} or Ca^{2+}, electrostatic interaction, ligand exchange, surface sorption, complexation with functional hydroxyl groups and anion exchange [66].Rosales et al. [67] reported that the chemical composition of the biochar surface is of importance for removing nitrogen since oxygen-groups generated during low-temperature pyrolysis will increase the cation exchange capacity (CEC), thus increase removal of N. Acidic and functional phenolic and carboxylic groups are assumed to promote ammonium [67]. Beckinghausen et al. [62] concluded that the adsorption capacity is dependent on the feedstock used for production of biochar. Further, it was concluded that the feedstock used reacted differently even though the treatment conditions were the same.

2.2.1.3 Removal of organic pollutants in wastewater

Organic pollutants (OCs) in wastewater include dyes, phenolics, pesticides, polynuclear aromatics and antibiotics. Application of biochar has been considered as a promising solution for removing organic compounds in wastewater, due to the high availability of feedstock for biochar production, the simplicity of the preparation methods, and the biochar's unique physico-chemical properties [15,68]. Applications of biochar for removal of various organic pollutants from water have been investigated [15,30,33,35,68–71]. In general, the efficiency of biochar to remove and capture organic pollutants is heavily affected by its microscale physical properties (specific surface areas and pore size distribution), surface functional groups and hydrophobic nature. Owing to the high specific surface area and micropores volume of biochar, the organic pollutants can be adsorbed though physical settling and precipitation and pore-filling routes, where the pollutants settles and forms layer on biochar surface and condensation of pollutants with resulting filling of pores of the biochar. Again, the specific surface area, total pore volume and size of the pores of biochar are largely dependent on properties of the raw biomass and production conditions. For instance, biochar produced at high temperatures has larger surface and more micropores, making it more suitable for organic pollutants removing and adsorption [72,73]. The adsorption capacity of biochar also depends on types and amounts of surface functional groups, which affect the hydrophobic nature of biochar. Qambrani et al. [15] stated that O-H, -CH_2, CO=, CC= and -CH_3 are main functional groups formed on the biochar surface upon various conditions. With lower oxygen- and nitrogen-containing functional groups, the biochar is more hydrophobic, which favors adsorption of insoluble adsorbates. In addition, hydrophilicity/ hydrophobicity of the biochar is often related to amount of polar-group on surface of biochar. The molar oxygen to carbon (O/C) mole ratio and hydrogen to carbon (H/C) mole ratio have been considered as an indicator of carbonization degree and abundance of polar functional groups on biochar [74]. The biochar produced at higher temperature has lower O/C and O/H mole ratio, indicating the biochar surface is more aromatic and hydrophobic with high adsorbing affinity to organic pollutants. Hale et al. [75] compiled biochar adsorption data for neutral organic compounds from twenty-nine different studies. The general findings are that biochar with larger specific surface area has stronger capability to adsorb neutral organic compounds, while the adsorption capacity decreases with increasing O/C and H/C mole ratio of biochar at higher OCs concentration.

In addition, the performance of the biochar as adsorbent is considerably related to solutions pH and size of organic compounds to be adsorbed. The pH value of the solution affects the surface charge of biochar and ionization of absorbate. In solutions with different pH values, the behaviour of surface functional groups (mainly oxygen-containing groups, e.g., carboxylate, COOH and hydroxyl, OH) on bichar can considerably vary. It consequently affects adsorption mechanism and process of specific organic pollutant on biochar surfaces [76]. At higher pH and, in particular for polar organic pollutants, the phenolic -OH groups were dissociated creating a negative charge on the biochar surface, increasing the electrostatic interactions with the adsorbed molecules. Adsorption experiments reported by Essandoh et al. [77] showed that with increasing solution pH from 2-3 to 10, biochar became increasingly negatively charged, causing an increase in the electrostatic repulsion and decrease of adsorption capacity. However, at pH of 6 and 8 for ibuprofen and salicylic acid respectively, the sorption capacity reached a maximum and then dropped as pH increased [78]. An increase in the number of negative charges with increased pH was observed by Xu et al. [79]. Rise of pH led to an increase in the dissociation of the phenolic -OH group, which made the negative charge of the biochar even more negative resulting in an increase in the electrostatic attraction between the biochar and adsorbate. Similar results were also reported by Shang et al. [76] who used biochar to remove ciprofloxacin.

2.2.2 Application in soil

Biochar has been considered as a promising solution to mitigate soil infertility and desertification as well as climate change. Studies about applications of biochar in soils have been summarized in Table A2 in Appendix A. Comprehensive studies have demonstrated the many benefits of biochar as soil conditioner to improve soil quality, promote plant growth and increase crop yield [49]. Other studies have also focused on the role of biochar in climate change mitigation [80] and remediation of polluted soils [81].

2.2.2.1 Soil fertility enhancement

Biochar contains high content of inorganic elements that can sever as macro and micro plant nutrients, which can act as a direct fertilizer and improve plant growth [49,82]. Several studies have showed that biochar application to low fertility soils may substantially enhance crop production [23,26,83,84]. Although the total content of nutrients such as N, P and K in biochar may not necessarily reflect the availability of those nutrient to plants [85], it can be used as an indirect indicator to select the most suitable biochar to enhance soil fertility [49,86]. Purakayastha et al. [45]reported that biochar produced at lower temperatures enhance availability of mineral nutrients in soils. Addition of biochar can also improve the soil environment and quality, bulk density, porosity, water retention and hydraulic conductivity [45]. Moreover, addition of biochar can increase the cation exchange capacity of soils and have positive effects on soils fertility and stability [37,87,88], which enhances root condition and morphology so that plants can exploit larger soil volumes [82]. In general, soil CEC is directly proportional to soil pH. For the soil with neutral or basic pH, anionic nutrients are poorly bound, which can be easily leached or flushed from the soil into ground waters. With long time cultivating and harvesting, the soil suffers deficiency of nutrients. Thus, to fulfil the shortage of nutrients, a large amount of chemical fertilizer is added to the soil, leading to deterioration of the environment. The biochar amendment to the soil has proved to be beneficial to improve soil fertility and retain nutrients, thereby enhancing plant growth. Normally, biochar with a higher pH value was applied to the soil, the amended soil generally became less acidic. Moreover, addition of biochar not only increases the K concentration in soil, but also increases plant nutrient use efficiency (NUE). Biochar can also stimulate soil microbial population and activity, particularly mycorrhizal fungi [89], which are critically important for nutrient cycling [90]. However, all these benefits are strongly related to the biochar type and soil properties. SSA is of high importance as it increases biochar capacity to adsorb organic compounds and metal ions, which can further improve the use efficiency of fertilizer or nutrient [49,58,91]. In general, the biochar with high SSA and porosity has high affinity to nutrients, which are beneficial for retaining moisture and nutrients in the soil for crop growth. In addition, the porous characteristics of biochar as well as its heterogeneous surface functional groups can take part in diffusion of nutrients in soil. Therefore, as highlighted by Ding et al. [49], the favourable properties of biochar to improve soil fertility are high specific surface area and porosity, rich in active organic functional groups andhigh content of available nutrients. In addition, Schmidt et al. [92] reported that freshly produced biochar might decrease the crop yield due to the nutrient immobilization process. Biochar produced at relatively high temperatures were found to be efficient in neutralizing soil acidity and promoting soil nutrient retention [93] while biochar produced at relatively low temperature mainly improve soil cation exchange capacity [94]. In addition, for the purpose of increasing soil fertility, nutrient-rich biochar produced from e.g. manure or sludge biomass, are the most suitable [95].

2.2.2.2. Soil remediation and amendment

Soil remediation is used to control, modify or destroy pollutants that can pose potential risks to the environment and human health [96]. Biochar is considered a suitable material for soil remediation purpose, and can be used to immobilize and transform soil pollutants, such as organic contaminants, heavy metals, PAHs and other toxic compounds, given its large specific surface area, porous structure and abundant surface functional groups [96]. The effecicency of biochar for soil remediation is closely related to the biochar and soil properties, amendment conditions and contaminant type [95]. Several studies have shown that the capability of biochar to remedy pollution relates to physical adsorption on the surface and in micro-pore structure [97]. In addition, the functional groups on biochar surface play important roles in the immobilization of heavy metals in the soil [1,98]. Other studies have pointed out that organic components [99] and alkaline minerals contained in biochar [100] also have an important role in stabilizing heavy metals in soils. Biochar can also be used to amend acid soils [101] resulted from e.g. excessive utilization of fertilizers. As most of the biochars are alkaline, they can be used to increase the pH of soils and thus affect the nutrient bioavailability, increase the capacity soil to hold water and enhance soil quality [45,83]. pH of biochar depends on the content and form of ash forming elements, which is significantly correlated with properties of biomass. Biochar produced from wood has onaverage a lower pH value than those produced from non-wood-derived biochar. In addition, higher pyrolysis temperatures also favor the production of biochar with higher pH values [100]. It could be attributed to enrichment of non-pyrolyzed inorganic elements as a result of decomposition of the organic matrix.

Extensive use of pesticides and herbicides in agriculture is deteriorating the soil quality in some parts of the globe. Safaei Khorram et al. [102] emphasised the need for environmentally sound remediation methods that can both (i) bind pesticides and reduce their motility into water resources and living organisms and (ii) provide nutrients to promote plant growth and improve soil quality. Biochar can meet those requirements as it can reduce the bioavailability of pesticides [1]. Several authors have reported that the adsorption capacity of biochar for pesticides and herbicides depends mainly on its physico-chemical properties, including organic carbon content, specific surface area (SSA) and porous structure [103,104]. Therefore, biochar produced at higher temperature tend to exhibit higher efficiency for absorbing organic contaminants in soils, as is the case for pesticides and herbicides. Furthermore, biochar with small particle size (<2mm) has much higher capacity for pesticides adsorption [105]. In addition, the plant uptake of pesticides can be decreased with increasing biochar application in the soil [106]. With addition of biochar, pesticide will be adsorbed on biochar surfaces, which is not in the bioavailable fractions of the soil pore water environment. Therefore, pesticide uptake by plants cultivated in biochar amended soil can be considerably reduced. Adsorption is normally the key mechanism involved in capturing of pesticide by biochar. Biochar has been proven as an efficient sorbent for several groups of pesticides. There are several studies showing that biochar amendment can lead to irreversible adsorption of the tested pesticides [81,103,107]. On the other hand, desorption of pesticide from biochar can occur due to deformation of macropores, or loss of binding between pesticide and biochar [102]. Addition of biochar effects mobility of pesticides and reduce leachability of pesticides in soil. Remarkable reduction of several types of pesticide in biochar amended soil has been reported, which was mainly attributed to entrapment and accumulation of pesticide inside and around biochar particles. Presence of biochar also affect biodegradation of pesticides in along time prospective. Nonetheless, direct evidence is still to be gathered for different biochar properties.

There are many harmful pathogens from domestic waste and radioactive substances that may accumulate in the soil. The capacity of biochar to adsorb them has not been well studied [108]. Besides the biochar characteristics, the efficacy of biochar in soil remediation varies with soil type, amendment rate and target contaminant. Therefore, several authors suggest that biochar characteristics cannot be generalised for a specific application but instead a biochar selection should be made on a case-by-case basis [1,95,109,110].

2.2.3 Carbon sequestration

Production of biochar is a promising option to sequester carbon from plant materials, taking it out of short-term carbon cycle and binding CO_2 with long-term storage of carbon in soil. The potential of carbon sequestered in soil is closely related to: (1) yield of biochar and carbon content in the biochar, (2) content of stable carbon in the biochar and (3) stability of biochar in soils under different conditions and time-frames.

The amount of carbon sequestered through burying biochar in the soil primarily depends upon yield and carbon content of biochar, which are heavily conditional on properties of the feedstock and pyrolysis conditions. Typically, biochar yield decreases with increasing pyrolysis temperature, accompanied with increase of gaseous and liquid products at higher temperatures. On the other hand, the fixed carbon content of produced biochar increases with high production temperature. Therefore, a more meaningful measure of the biochar production efficiency has been given by the fixed carbon yield $y_{FC} = y_{char} \times [FC\%/(100 - feed\_ash\%)]$ [111], where y_{char} is the char yield from pyrolysis process, *% feed ash* is the ash content of the raw biomass and FC is the fixed carbon content of biochar. The fixed carbon yield corresponds to the efficiency of converting carbon in the biomass to the biochar, which can be used as an indictor of the carbon sequestration potential of biochar [111].

The other key factor affecting carbon sequestration potential of biochar is the percentage of stable carbon content [112]. The stability of biochar has been assessed by different methodologies through either individual or combination of analytical techniques [113–115]. The content of stable carbon in biochar can be considerably influenced by the production conditions and properties of the feedstock. With increasing production severity, including highest treatment temperature (HTT), residence time and slow heating rate, the stable aromatic carbon content in the biochar has higher stability in soil and carbon sequestration potential. From a production point of view, pyrolysis temperature is a dominant parameter which affects the stability of biochar. In addition, properties of biomass feedstock, such as biochemical compositions and contents of inorganic elements, also play important roles affecting the stability of biochar. However, there is a need to consider the trade- off between biochar yield and stability. Both yield and stability of biochar greatly influence carbon sequestration capacity of biochar, which determines the actual amount of carbon that can be stored. Therefore, production process parameters need to be optimized for producing biochar with high stability and without significantly sacrificing of the biochar yield. On the other hand, biochar produced from different feedstocks but under the same process conditions have different stable carbon contents. Generally, biochar produced from a feedstock with high lignin content, often has a high content of aromatic carbon and slower mineralization rate, which have a high stability in the soil and a long-term carbon sequestration potential [116]. There are several methods that have been developed for assessing stability of biochar produced from a wide range of biomass and under different conditions. For example, the stability of biochar can be measured by using both O/C and H/C mole ratio as indicators. O/C was proposed by Spokas et al. [117] for biochar stability in soils. For example, biochar with an O/C of 0.2 was considered very stable, possessing an estimated half-life of 1000 years. However, Budai et al. [118] suggested that the H/C mole ratio is preferred over the O/C, because H is determined experimentally, while O is calculated, which may lead to overestimation. The results from studies applying these methods can be used to assess carbon sequestration potentials of different biochars and optimiz production conditions to obtain biochar with high stability biochar. Using biochar as a carbon sequester is based on the assumption that stable carbon in biochar can persist in soil for hundreds or even thousands of years. Once applied to soil, biochar undergoes aging and degradation processes, including wetting-drying cycles, photochemical irradiation and mild oxidation [5]. It leads to considerable changes of physicochemical properties of biochar, which causes either enhancement or detriment of biochar’s performance for carbon sequestration purpose. Therefore, the physicochemical properties of biochar produced in a specific process will significantly affects itslong-term environmental behaviours and carbon sequestration capacity. However, the long-term behaviour of biochar in the soil has not been well studied and summarized, since nature conditions are complex, and there are many factors that can affect the properties of biochar. Therefore, it is not clear whether there is a direct relationship between the behaviours of biochar and carbon sequestration potential from a long time prespective, which needs to be further explored.

2.2.4 Biogas production

It has been reported that addition of biochar is an efficient way to improve anaerobic digestion (AD) through (i) enhancing yield of biogas and methane content, (ii) adsorbing inhibitors, (iii) colonizing microbes selectively and (iv) alleviating inhibition of ammonia [41]. The enhancement degree is often associated with the biochar properties. It has been reported that microstructure, surface chemistry and content of microelements and pH of biochar are important properties that its role during AD, which has been summarized in Table A3 in Appendix A.

During AD, ammonia forms as the main metabolic by-product and inhibit the methanogenesis. Biochar added to AD can adsorb the ammonia, as it has porous structure and large specific surface area. The adsorption of ammonia on the biochar surface is a dynamic process and involves different mechanisms, including physical adsorption, surface precipitation and complexation, pore filling hydrogen bonding, electrostatic attraction and ion exchange. The adsorbed ammonia can react with different functional groups on biochar surfaces to form amines and amides. This will reduce accumulation and mobility/bioavailability of the ammonia as a direct inhibitor without affecting the AD process. In addition to the direct inhibitor, there are also indirect inhibitors such as volatile fatty acids (VFAs) formed during the AD process. The accumulation of VFAs results in low pH and reduce the buffering capacity of the system. Addition of alkaline biochar can be used to regulate the pH value in the AD system and increase methane yield.

It is common to use alkaline biochar to regulate the pH value in the AD system [42]. Fagbohungbe et al. [119] reported that using biochar with pH of 6.9 can increase biogas production. Qiu et al.[43] also observed that the alkaline biochar increased biogas production by adding 15–20% of biochar. Wang et al. [44] added biochar from Holm oak residue with a pH of 8.96 to the AD of municipal biowaste and observed an increase of biogas production of 5% per dry matter due to 5% biochar addition. The impacts of the properties of biochar on biogas production are summarized in Table A3 in Appendix A.

Addition of biochar can also improve biogas yield from AD through enhancing colonization of microbial cells on the polymerised biochar surfaces[48]. Biochar with porous structure provides a large solid surface available for physical adsorption of microbial communities that are critical for facilitating electron transfer between interspecies. The structure and pore size of biochar are important for determining the capacity of biochar to immobilize microbial cells. Biochar has also the potential to promote co-metabolism of anaerobic microorganisms. The syntrophic partners for biogas production involve an indirect interspecies electron transfers mechanism [45]. Kalus et al. [46] evaluated the impacts of biochar addition on AD. The results show that the amount of trace elements in biochar, such as K, plays a key role in enhancing biogas production. The supplementation of trace elements through biochar enhanced the biogas production of the food waste by 8.5% [48].The ash content is an indicator of the amount of alkali metals remained in the biochar [48,120]. Alkali metals in biochar can improve the resistance of the anaerobic system and maintain the syntrophism between acetogenic and methanogenic bacteria.

Detailed information about the effect of properties of biochar such as SSA and pore size distribution on biogas production are lacking from the scientific literature and the quantitative effect of other single properties as mentioned above are still not well studied.

2.2.5 Gas cleaning

Biochar can be used for gas cleaning purpose, due to its low-cost and adsorbent properties, including SSA and pore volume. There have been many studies using biochar to adsorb NO_x and H_2S, as shown in Table A4 in Appendix A. The adsorption capacity of biochar increases with the increase of SSA and pore volume., activation and/or surface functionalization are two measures normally used to further enhance adsorption capacity of biochar. For example, after the biochar was activated by using steam treatment (700–850℃, 1–7 h), NO_x removal rate was increased from 10% to 46% [57]. NO_x removal efficiency of different biochar can be further enhanced through a simple treatment that creates oxygen functional groups on their surface, which assistes the chemical adsorption of NO_x [1,35,51,68]. Cha et al. [14] used FT-IR spectra for identification of the functional groups of biochar. The highest efficiency was obtained when the C=O and C-O functional groups increase in biochar due to chemical activation. Choudhury and Lansing studied the performance of biochar addition with Fe impregnation for in-situ desulfurization of biogas [121]. Corn stover biochar (CSB) and maple wood biochar (MB) were tested, and results showed that the Fe-impregnated biochar (0.5 g biochar/g manure TS) reactors had no H2S detected in the CSB-Fe system.

The capability of using biochar to remove gas components is not limited to NOx and H_2S, but a limited number of studies have been made on other gases. Regardless of the potential to use biochar for gas cleaning, biochar's adsorption capacity and selectivity towards the desirable feedstock still needs to be improved.

2.2.6 Biochar as catalyst

Biochar shows great potentials as a versatile catalyst in many chemical processes. Biochar can be used as catalyst in biodiesel production through esterification. Impacts of SSA, pore volume and acid functional groups of biochar on the reaction activity during biodiesel production are shown in Table A5 in Appendix A. Due to its characteristics that include high porosity and carbon content, it is promising to use biochar to replace conventional solid carbon-based catalysts [56]. In general, increasing SSA results in an increased transesterification yield. As reported by Yu et al. [122], the reaction yield was more than doubled when SSA of biochar increased from 1.88 to 640 $m^2 \cdot g^{-1}$. It can also be observed that the production of fatty acid methyl ester (FAME) can benefit from presence of acid functional groups on biochar surfaces [57,123]. Experimental results reported by Li et al. [124] and Lee et al. [34] showed that biodiesel production increased, which is partially related to generation of $–SO_3H$ groups during the production process as biochar with higher SSA was introduced. Moreover, when the pore volume of biochar was approximately tripled the conversion rate of free fatty acids for free fatty acids (was increased by 27%, which can also contritbue to increase of biodiesel production capacity [125]. The biochar is also a potential photo catalyst in the degradation of organic pollutants as reported by Kim and Kan [126]. The study suggested that the catalytic activity of biochar can be affected by the different properties, such as pore structure, pore distribution and surface functional groups.

2.2.7 Application in the metal industry

Biochar can be used to replace coke in the metallurgical industry as a reducing agent and fuel [127]. Studies about the applications of biochar in metal industry have been summarized in Table A6 in Appendix A

Biochar has been studied and tested as a promising alternative to conventional fossil reductants. Fixed carbon and volatile matter contents are two important properties, as the biochar is used as reductant in metallurgical processes. As metallurgical reducing agents, biochar with high FC and low VM are often required. The fixed carbon and volatile matter of typical reducing agents used in metallurgical processes are 83.6% and 3.9% (<8.75) respectively [128]. The presence of a high amount of VM results in an easier and more rapid ignition, at lower ignition temperature [129–131]. Biochar with high VM content also generates large amount of combustible gases that are difficult to control and clean. The SSA and micropore volume of typical reducing agents used in metallurgical processes in rotary kilns is 24–156 $m^2 \cdot g^{-1}$ and 0.01–0.07 $cm^3 \cdot g^{-1}$ respectively [123,132]. Biochar withlarger SSA and porosityoften has higher reactivity and coverted fast in metallurgical processes. It has been reported, the reactivity of biocharincreased by around 10% when SSA and micropore volume increased from 363–501 to 444-501 $m^2 \cdot g^{-1}$ and 0.15–0.21 to 0.19-0.21 $cm^3 \cdot g^{-1}$ [132].

Biochar can be used to replace fossil fuels in the blast furnace for iron production. Sun et al. [133] found that using biochar with relatively high fixed carbon content and large particle size (1–5 mm) in the sintering process, a similar sinter yield and productivity to that obtained by using coke breeze can be obtained. The blast furnace requires fuels with high heating values and carbon contents as well as high grindability and densities. Typical blast furnace fossil fuels, such as pulverized coals have a carbon content of 80–90%, an ash content of around 10% and a heating value of around 30 $MJ\cdot kg^{-1}$ [134]. In addition to utilization in iron production, the biochar with properties can also be used for ferroalloy metal production. Mechanical properties of biochar are crucial considering mass loss and generation of fines during transportation, handling and further feeding in and flowing in the furnace. In addition, low mechanical strength of biochar is often associated with high porosity and large surface area, which gives unwanted high reactivity during metal production process. The studies reporting test and assessment of mechanical strength of biochar are rather seldom. In one recent published paper, the mechanical properties of coal, petroleum coke and biochar produced from hard and softwood are compared [135]. The biochar produced from biomass materials have rather poor mechanical strength (indicated as compression strength), which is about of that of metallurgical coke. With considering of this, different measures have been developed and tested to improve and increase mechanical strength of the biochar. Riva L et al., conducted series tests to making pellets out of biochar produced under different conditions and studied effects of pelletization conditions on mechanical properties of produced biochar produced pellets [134,136]. The results showed that mechanical properties (i.e., compression strength) of biochar pellets produced with using certain types of binder can be significantly enhanced, even comparable with fossil fuel pellets and briquettes. Further work is needed for testing mechanical properties of biochar under conditions relevant to industrial operational processes and investigating methods to improve mechanical strength of biochar with least efforts.

2.2.8 Electrochemical applications

Some studies about using biochar for electrochemical applications have been summarized in Table A7 in Appendix A. Electrodes are essential components in microbial fuel cells, which facilitate exo-electrogenic biofilm growth and electrochemical reactions. Biochar as an electrode could be a cost-effective and environmentally friendly option. High specific surface area, high conductivity, low cost, stability, and biocompatibility are the desired properties when selecting materials [137]. In addition, high carbon content in biochar is presumably beneficial for high power density, provided that the ash content is kept at an acceptable level. Ash is a matter of concern because it impedes the ionic conductivity, and therefore, reduce the output power [138,139].

Biochar is being used as an electrocatalyst and photocatalyst for hydrogen and oxygen production via water-splitting [140]. With the increase of the specific surface area, the current density increases. However, SSA is not necessarily the only property that determines its electrochemical reactivity. the chemical degree of carbonization is another important factor, which is primarily represented by H/C and O/C atomic ratios [141]. Doping with heteroatom creates active sites in biochar for enhanced hydrogen evolution reaction (HER). For example, S-doped and N-doped biochar derived from peanut root nodule have been reported to be an efficient electrocatalyst for the HER [141].

Modern supercapacitors are endowed with excellent reliability, high power density, and fast charging and discharging characteristics. Due to the high specific surface area, biochar is regarded as a candidate material to fabricate electrodes for supercapacitor applications [142,143]. In addition to SSA, pore sizes distribution (micropores: same size as ions in electrolyte for higher energy density; macropores/mesopores: fast electrolyte diffusion for higher power density) and wettability are other key properties related to such an application [144,145]. The activation process on the biochar improves its SSA and pore fraction/distribution to meet the demand for energy storage and conversion processes. Modifications based on metal, metal oxide and metal hydroxide loading and nitrogen and sulfur doping are also favorable [146].

Cost-effective and sustainable synthesis of biochar and its high specific charge storing capacity compared to conventional graphite materials, makes it desirable for various kinds of rechargeable batteries [147]. Similar to the application of supercapacitors, the optimal pore size distribution is of importance as sub-nanometric pores favour ion diffusion. High N content is also preferable, since neighboring C is more electronegative, which is prone to intercalate Li [144]. However, the key influential properties of biochar for battery applications are not well-known due to the lack of systematic studies with mechanism understanding.

3. Impacts of feedstock and production conditions on biochar properties

3.1 Feedstock and operation conditions

Biomass materials come from a wide range of sources with various properties. Although there is no univocal way to categorize biomass materials, attempts have been made to group them according to typical properties for summary and comparison purposes. The categorisation of biomass materials is often based on their physicochemical properties, organic and inorganic compositions, and they can have rather similar conversion behaviours under certain conditions. Considering this, and following recommendations in the literature [22,148], and based on the biomass used in the studies on biochar production reviewed in this paper the biomass can be categorized into the groups shown in Table 4. Woody biomasses (WD) include stem, branch and bark of different tree species. Herbaceous biomasses (HB) are referred to those derived from a wide range of agricultural crops, including stalks, straw, shells of the crops etc. Biosolid sludge (BS) derived from wastewater treatment and biogas production processes is another group of feedstocks. Biosolid sludge has considerably different properties than the conventional biomasses, including high content of water, ash, nitrogen and heavy metals. Animal and human waste (AW) includes manure from animals, food waste, paper, plastics, pulps and others.

Table 4 Groups of biomass feedstock used for biochar production

Groups	Common feedstock
Woody biomass (WD)	Stem wood chips, sawdusts, shavings, bark, logging residues, forest residues, twigs, etc.
Herbaceous biomass (HB)	Switchgrass, stalks, straw, stover, grass, bamboo, oil palm shells, etc.
Animal and human waste (AW)	Poultry litter, manure, swine solids, chicken manure, food, fruits, paper, plastics, pulps, etc.
Biosolids sludge (BS)	Sewage sludge, digestion sludge, etc.

In general, biochar can be produced from processes with different production condition, including torrefaction (200-350 °C), pyrolysis (350-1000 °C) and gasification (700-900 °C), as shown in Fig.1. For these thermochemical conversions processes, biochar properties are significantly affected by temperature, heating rate and residence time.

Table 5 Technology for producing biochar from biomass materials

Production process	Production condition			Typical biochar yield (wt%)
	Temperature	Heating rate	Residence time	
Torrefaction	200-350°C	1-20 °C/min	10-60 min	75-90%
Slow pyrolysis	350-700°C	0.5-20°C/min	Minutes to days	25-35%
Fast pyrolysis	700-1000°C	10–200 °C/s	0.5–10 s	12–15%
Gasification	700-900°C	5-30 °C/min	Seconds to minutes	5-10%

3.2 Properties of biochar produced from torrefaction

The properties of biochar produced from torrefaction are summarized in Table B1 in Appendix B.

The torrefaction temperature can significantly affect the yield and the properties of biochar [90]. With increasing temperature, the yield of biochar and the content of volatile matter, elemental oxygen, hydrogen, and nitrogen of the produced biochar decreases, whereas HHV, FC and ash content increases. In comparison to torrefaction temperature, residence time gives similar but less pronounced impacts on the properties of the biochar.

3.3 Properties of biochar produced from pyrolysis

The reviewed properties of biochar produced from pyrolysis are summarized in Table B2 in Appendix B.

3.3.1 Slow pyrolysis

For slow pyrolysis, the highest treatment temperature (HTT) and residence time have the most significant impacts on properties of produced biochar. Upon an increase in the pyrolysis temperature, the volatile matter content of biochar decreases with enrichment of fixed carbon. In addition, the surface properties and microstructure of biochar produced at diverse temperatures can be considerably different, which affect further applications [4] Increase in pyrolysis temperatures generally leads to biochar with larger pore sizes and higher specific surface areas [122,150]. As reported by Zhao et al. [149], when pyrolysis temperatures increase above 400°C, the biochar specific surface area gradually increases and at 600°C the highest SSA was achieved for all the feedstock tested. On the other hand, SSA of biochar can decrease upon further increase of the pyrolysis temperature, which may be due to restructuring of carbonaceous structure and re-blocking of micropores. Compared to other feedstock groups, biochar produced from woody biomasses often have higher SSA and the impacts of temperature on SSA of biochar produced from WD are more significant.

The data presented in Table B2 in Appendix B suggest that an increase in the temperature leads to greater losses of elemental H and O when compared to that of C. It is mainly related to dehydration and decarboxylation reactions during decomposition of biomass material [15,149,151]. As a result, mole ratio of H/C and O/C of biochar decline as biochar produced at higher pyrolysis temperatures. Large differences in elemental composition can be observed among biochar produced from different biomass materials at lower pyrolysis temperature, i.e. lower than 600°C. At a pyrolysis temperature of about 750°C, there is a convergence of H/C to 0.18 for most of the studied biomass materials. Comparatively, WD has the highest H/C while BS has the highest O/C. Since, biochar produced from torrefaction is mainly used as fuel, there are few studies about physical properties, such as SSA and pore size.

The pH-value of biochar increases evidently with the rise in pyrolysis temperature due to the enrichment of non-pyrolyzed inorganic elements and the presence of salts, such as carbonates and chlorides of potassium and calcium [150]. Most of the biochar is alkaline, with a pH between 8.2 and 12.4, as shown in Table B2 in Appendix B. For pyrolysis temperatures above 500°C, the pH value of biochar produced from different biomass materials can be in the range of 10 -12. In addition, and compared to other feedstock groups, biochar from BS normally has higher pH than the biochar from other biomass groups. The increase of biochar pH can also be due to the release of acid functional groups and polymerization/condensation reactions of aliphatic compounds [23,26]. The biochar produced from different feedstock also have various pH values. For example, biochar produced from WD has a lower average pH in a solution than that produced from other feedstock groups at similar conditions. Biochar produced from BS exhibited the highest pH values, corroborating with the higher amount of basic salts found in its feedstock [25]. The pH of biochar is related to the presence of oxygen functionalities. Under lower process intensity, more labile – and more oxygenated – carbon can be retained.

3.3.2 Fast pyrolysis

In fast pyrolysis, the pyrolysis temperature has similar impacts on biochar properties as observed with slow pyrolysis conditions. For example, there are peak values for H/C and O/C ratios when temperature changes. However, the peak appears at lower temperatures [152]. The effect of pyrolysis heating rate on biochar yield is more obvious at low pyrolysis temperatures. For example, the investigation of Lehmann et al. [153] showed that for the pyrolysis of beech trunk bark there was a noticeable effect of heating rate on biochar yields and the result was more pronounced at lower temperature ranges. A high heating rate can enhance the depolymerization of biomass into volatile components, which decreases the biochar yield. As shown in Table B3, the decrease of SSA at slow heating rates was faster than at high heating rates. This can be explained by the release of volatiles. Higher heating rate can reduce the time for the volatiles to be released, which results in an accumulation of volatiles between and within particles. Heating rate has also a clear effect on pH of the biochar from fast pyrolysis, which is in a range of 7.59 to 10.15, and is normally lower than that of the biochar from slow pyrolysis [101].

3.4 Properties of biochar from gasification

The primary goal of gasification is to produce gaseous products. Therefore, the yield of biochar from a gasification process is lower than the one via slow pyrolysis. On the other hand, due to the higher conversion temperature and presence of gasification agent (i.e., CO_2 or air), biochar from gasification has higher specific surface area and porosity and ash content. The specific surface areas of biochar derived from different feedstocks under gasification conditions increased as the temperature increases. Biochar from WD has the largest SSA, as shown in Table B4. Similar observations have been reported by Bruun et al. [154]. As shown in Table B4, all biochar from gasification was found to be alkaline ($9.3<pH<13$) due to the high ash content, with the exception of biochar produced from WD, which was acidic. [154]. Biochar from BS usually has a larger pH than other feedstocks. Biochar from WD has the largest variation in volatile matter, as shown in Table B4, whereas biochar from animal waste showed the smallest variation. The heating value of biochar increases with increasing gasification temperature, which is more obvious for WD biochar. WD biochar has shown higher HHV than other feedstocks. The presence of C-H, C-O and O-H bonds remaining in the biochar is found to influence the HHV of biochar [4]. The properties of biochar produced from gasification are shown in Table B4 in Appendix B.

3.5 Modification of the biochar properties

To adapt the properties of biochar to different applications, many methods have been studied, tested and developed. In general, the methods include chemical and physical modifications, which can be conducted before, during or after biochar production. Chemical modifications have been widely tested, including chemical oxidation, alkalinity modification and metal salts agent modifications. Physical modifications mainly include activation through purging and reacting steam and gas agents. Table B5 in Appendix B lists the change of biochar properties after different modification treatment.

3.5.1 Chemical methods

3.5.1.1 Acid modification

The main purpose of acid modification is to remove the impurities and increase the oxygen-containing functional groups such as -OH and-COOH. The commonly used oxidants for biochar activation are HCl, HNO_3, H_2O_2, H_3PO_4, etc. Upon acid modification, the pore size and structure of the biochar can also be changed, and the effect on microstructure and specific surface area varied with the type and concentration of the acids. The properties of acid modified biochar are also closely related to the feedstock and preparation conditions. The adsorption capacity of biochar and its role in different applications can also be affected.

3.5.1.2 Alkaline treatment

The main purpose of alkaline treatment is to increase biochar specific surface area and amount of the oxygen-containing functional groups. The common alkaline agents include potassium hydroxide and sodium hydroxide. Potassium hydroxide [155], ammonium hydroxide [156] andsodium hydroxide [157] are common alkaline agents used to increase SSA and porosity of biochar [158]. Again, the effect of alkaline treatment on the specific surface area of biochar is also affected by the type of feedstock and production conditions. For example, using KOH (KOH: biochar = 1:1, 60℃, 2 h) followed by calcination (700℃, 1 h) can successfully expand SSA of biochar derived from rice straw and sewage sludge from 140 to 772 $m^2 \cdot g^{-1}$ and from 18 to 783 $m^2 \cdot g^{-1}$, respectively. Cha et al. [159] used NaOH treatment to increase SSA, ion-exchange capacity, and the number of oxygen-containing functional groups of biochar. In another study, sodium hydroxide modification had no effect on the specific surface area of bamboo-derived biochar [160] .

3.5.1.3 Metal salts or metal oxides modification

Development of metal salts or metal oxides for modifying the properties of biochar, has gained interests in past years. With this modification method, the key biochar properties can be changed and as a result its characteristics including adsorption capacity, catalysis strenghth and magnetism can be improved. Zinc chloride has been used to increase porosity, specific surface area and adsorption capacity of biochar [161]. Shen et al. [162] tested different activation temperatures and impregnation ratios for activation of safflower seed press cake and obtained the best results, with a SSA of 800 $m^2 \cdot g^{-1}$, for the highest temperature (900 ℃) and highest ratio (1:4) tested. The increase of the P adsorption in an aqueous solution of the biochar produced from sesame straw activated by several different metal salts and oxides (MgO, $ZnCl_2$, and K_2SO_4), was investigated by Lone et al. [29]. The best results were reached with zinc chloride for the impregnation ratio 1:1 and activation temperature of 600 ℃, which was the highest temperature tested. A higher impregnation ratio of 1:3 did not lead to a higher SSA (370 $m^2 \cdot g^{-1}$) or pore volume (0.230 $cm^3 \cdot g^{-1}$). Yazdani et al. [163] treated biochar from pinecone biomass with NaOH and $ZnCl_2$. (impregnation ratio 1:2 and temperature 800 ℃) and obtained a SSA of 1470 and 1068 $m^2 \cdot g^{-1}$, and a pore volume of 0.705 and 0.511 $cm^3 \cdot g^{-1}$, respectively.

3.5.2 Physical methods

Physical activation usually exposes biochar to a flow of gasifying agents, e.g., steam, CO_2, air and ammonia, at high temperatures. Gas purging modification can cause changes in the biochar properties mainly through two ways: (1) further release and loss of volatiles and condensates of biochar and (2) reaction of biochar towards gasifying agents with consumption of carbon [34,164]. Upon modification, the porosity and the specific surface area of biochar can be significantly increased while more pores can be formed with improved micro-porous structure.

The data in Table A5 suggest that SSA, pore volume, pore size and pH can be considerably changed with variations in the temperature and residence time. For example, the SSA of WD biochar can increase from 429 to 621 $m^2 \cdot g^{-1}$ when the residence time of gasification with purging of CO_2 is increased from 0.5 to 1 h [165], and from 435 to 687 $m^2 \cdot g^{-1}$ when the temperature is increased from 750 to 920°C [165]. Moreover, the pore volume of the biochar increased from 0.18 to 0.3 $cm^3\ g^{-1}$ with an increase in temperature from 750 to 920 °C [165]. The pH of Karanja kernel-biochar (generated at 300°C in N_2 for 4 h) decreased to half of its initial value when the temperature was increased to 500°C [125]. In general, the pore volume and SSA increases proportionally with an increase in the heating temperature while, the total acidity decreases with the temperature.

Steam gasification is one efficient way commonly used to modify biochar properties (i.e., specific surface area and porosity). Steam gasification of biochar is normally conducted in the temperature range of 700–850°C with different treatment time from 1 to 7 hours [126]. Upon steam gasification, a series of reactions take place between biochar and steam and other intermediate products (i.e., CO) from the biochar-steam gasification processes. These reactions cause consumption of reactive sites on the biochar surface, formation of new pores, enlargement and expansion of pores and activation of biochar consequently. After steam gasification, the surface area and total pore volume could increase up to one-order-of magnitude and increase of surface area as well [128]. For example, SSA of silk biochar can be increased 122–196 times after steam activation [166]. In addition, steam gasification of biochar can also be conducted with presence of other agents (i.e., H_3PO_4) with activation effects. It will further cause increase of micro porosity and pore volume of biochar, which can then used more efficiently for certain applications.

3.6 Summary of biochar properties from different processes

Table 4 summarizes the properties of biochar produced from different processes and different kinds of feedstock. Biochar yield decreased as the temperature is increased. The variation in the properties of biochar produced from different feedstock show very similar trends. It is also worth pointing out that the physical and chemical properties of biochar produced from WD, AW and HB are relatively close, but not from wastewater sludge (BS) [167].

As produced from slow pyrolysis processes, the SSA of biochar increases rapidly with the further increase of production temperature. As the temperature is over 700°C, the increase of SSA becomes less significant. Different than specific surface area, the porosity of biochar slightly decreases with as the production temperature is higher than 700 °C. This is more evident for biochar produced from woody biomass. In addition, biochar derived from woody biomass tend to have larger SSA when compared to chars derived from herbaceous biomass (Table A4).

With the increase of production temperature, pH of biochar produced from most of biomass materials included in the four groups linearly increased. It implies that temperature has dominant impacts on biochar pH. Most biochar is reported to be alkaline, but some biochar produced from WD, AW and HB may demonstrate neutral or slightly acidic, especially when the production temperature is lower than 400°C.

The ash content of the biochar generally rises with the increase of production temperature, whereas VM content declines. Biochar produced from AW shows the highest ash contents while biochar produced from WD show the lowest. Biochar from WD and AW shows the largest and smallest variations in VM respectively with increasing temperature.

The stability of biochar could be reflected by O/C and H/C mole ratios [117]. The O/C mole ratio is affected by processing temperature and type of feedstock. With increase of temperature, O/C mole ratio decreases almost linearly, because more labile structures of the feedstock are condensed and stabilized [4]. At the same time, the decrease of H/C mole ratio under high production temperatures is mainly due to loss of hydrogen as a result of de-hydronation and decomposition of biomass material. H/C mole ratio of AW biochar decreases faster with increase temperature, indicating different biochar formation behavior than other biomass materials. Moreover, under same production temperature, the H/C mole ratio of biochar produced from HB are the evidently lower compared to biochar produced from biomasses belong to other groups.

As listed in the Table 4, higher heating value of biochar increased as they are produced at high temperature, except for biochar from HB. As the production temperature exceeds 500℃, there are significantly increase of HHV of biochar produced from most biomass materials. The differences in HHV of the biochar formed from different materials are attributed to combustible content like carbon and hydrogen [6].

Table 6 Biochar properties produced from different processes and feedstock.

	Feedstock	Yield (%)	SSA ($m^2 \cdot g^{-1}$)	Pore Volume ($cm^3 \cdot g^{-1}$)	pH (%)	H/C (%)	O/C (%)	HHV ($MJ \cdot kg^{-1}$)	proximate analysis		
									VM (%)	Ash (%)	FC (%)
Torrefaction	WD	36.9-98	2.77-666.8	0.026-0-.323	5.7-8.1	0.08-12.6	0.18-88.62	19.6-28.4	41.99-80.35	0.3-7.87	16.54-50.40
	AW	42-95	1.4-7	-	7-9.3	0.19-15.62	0.2-103.5	19.8-24.56	47.12-90	7.6-46.5	16.46-25.02
	BS	42-91.2	0.7-66,58	0.012-0.057	5.3-6.17	0.33-12.18	1.05-83.1	27.25-30.58	33.14-70.81	1.9-52.33	9.91-19.48
	HB	30-94	0.6-211.63	0.022-0.031	6.97-9.19	0.09-15.04	0.1-95.55	20.0-26.76	30.52-81.02	0.7-22.9	12.46-54.56
Slow pyrolysis	WD	15.3-67	0.17-637	0.023-0.52	2.5-11.62	0.11-7.84	0.06-45.57	17-19	14.01-72.13	0.9-43.5	21.08-75.73
	AW	21-67.7	1.68-94	0.0013-0.0199	5.79-17	0.61-8.77	0.2-40.13	12-17	12.5-60.8	9-72.4	0.0-37
	BS	20-35	4.8-50	0.002-0.05	7.28-11.6	0.03-1.41	0.19-0.34	27.5-28	1.9-74.3	3.6-15.6	23.3-98.1
	HB	15-32	2.67-21.41	0.001-0.0067-	4.9-11.9	0.19-1.79	0.20-0.26	8.17-30.06	3.9-82.39	7.5-76.4	9.53-84.3
Fast pyrolysis	WD	14.4-58	0.19-540.63	0.015-37.87	4.7-11.62	0.17-1.46	0.03-0.7	-	2.61-83.44	0.3-41.8	9.64-91.55
	AW	30.6-72	0.57-401	-	7.3-10.3	0.20-8.03	0.05-70.4	14.75-20.9	18.3-80.7	14.8-59.6	4.5-36.3
	BS	52.4-72.3	0.1-13.3	0.0014-0.0066	4.87-12	0.2-1.54	0.07-0.41	15.07-21.12	13.0-73.6	20.9-72.5	5.6-33.8
	HB	11.4-34.18	0.29-0.57	0.0047-0.0069	6.1-11.2	0.19-1.43	0.05-0.75	28.15-30.27	3.26-79	2.73-21.25	9.70-80.70
Gasification	WD	0-95.5	78-1041.83	0.172-0.38	9.3-12	0.060-0.089	0.001-0.012	24.2-27.5	9.63-15.34	3.9-49.52	60.95-77.01
	AW	-	-	-	4.5-12	-	-	13-21.3	14.7-45	4.9-33.6	17-86
	BS	21.35-52.22	87-299	0.038-0.129	9.9-12	-	-	-	-	19-27	-
	HB	-	188-931	0.17-0.32	9.6-10.8	0.06-0.082	0.010.0.014	-	-	-	-

-.: not available.

4. Mapping the feedstock and production conditions according to the application of biochar

4.1 Correlation of biochar properties with temperature for different feedstock

Polynomial functions were used to fit the property data of biochar produced from different processes and different feedstock groups, in which the properties are functions of producing temperatures. The results are given in Appendix C and the corresponding curves are illustrated in Fig. 1 to 7. The square of correlation (R^2) is calculated for each regression to show the uncertainties. The confidential intervals are also added for each regression by using shades in different colors.

It is clear that for all groups of feedstocks, biochar yield decreases as the production temperature increases (Fig. 2). Comparing to the other three groups, the properties of biochar produced from BS differ more obviously. In general, the exponential curves well fitted the experimental data for all feedstock groups, which is similar to the results of Li et al. [6].

As shown in Fig 3, production temperature has clear effects on SSA of biochar produced from different biomass materials. As the production temperature is higher than 450°C, increase of SSA of biochar produced from woody and herbaceous biomass are more pronounced, as a result of severe degradation and decomposition of them at elevated temperatures. It implies that the dependence on feedstock type is prominent for SSA. Compared to the other groups, the regressed function for biochar produced from BS has a low R^2, which is R^2=0.3932.

As shown in Fig. 4 and 5, the changes of H/C and O/C mole ratios with temperature are quite different. For WD and HB, H/C generally decreases with the increase of temperature; while for AW and BS, it can go up and down. The regressions for H/C mole ratio all have a low R^2. This may be due to the diversity of AW and BS. There are also relatively fewer data compared to other properties. Differently, O/C mole ratio of surveyed biochar drops with the increase of production temperature for all feedstock types and all regressions have high R^2. Although these ratios don't have direct influence on the applications of biochar, they can reflect the stability of biochar.

With the increase of production temperature, pH of biochar produced from almost all types of feed-stock increases, as shown in Fig.6, even though R^2 of regressions are not very high. It further indicates that biochar pH is more sensitive to the process conditions than feedstock.

As shown in Fig. 7, with the increase of temperature, HHVs of biochar produced from different biomass materials increase, except those produced from AW, which decrease instead. The regression for WD has a high R^2 that implies a good consistency in this feedstock type.

Proximate properties of biochar are shown in the Fig. 8. The evaluation trend of volatile matter, fixed carbon and ash content are similar for all biochar produced from four types of biomass. In general, FC and ash increase with the rise of production temperature, whereas the VM content decreases. Biochar produced from AW and BS show clearly higher ash contents while lower FC than those produced from WD and HB.

4.2 Selection of feedstock and production processes

The selection of production processes and feedstock are suggested through checking if the properties of biochar match the required properties for different applications, which are summarized in Table 6. Despite the high interest in using biochar in a diverse range of applications, there are still knowledge gaps regarding the biochar characteristics, which need to be bridged, in order to promote biochar. The identified knowledge gaps are also highlighted in Table 6.

When biochar is used for wastewater treatment, high SSA, and numerous functional groups, mainly oxygen containing groups are required. However, there has been no quantitative comparison about the influences of different functional groups. pH value is also a key property, which is depending on the pollutant to be removed. In general, an acid environment is needed, but increasing pH favors the removal of heavy metal. To achieve a high SSA, high temperature is preferable. Whereas Fig.6 clearly shows that biochar produced in the temperature range of 200-400℃ has the most attractive pH. Therefore, 300-400°C is the most suitable biochar production temperature for wastewater treatment. Moreover, WD is the preferable feedstock while HB is not recommended. Since less data are available about pH of AW and BS at low temperatures, more measurements are needed in order to conclude if AW and BS are suitable feedstock.

As used for improving soil fertility and property, biochar with high SSA and pH are desired. It is clear shown in Fig. 3 and 6 that increasing the processing temperature can improve both properties. Therefore, gasification is superior to pyrolysis and torrefactionand HB is the most favorable feedstock. Even though biochar produced from BS and AW can have high pH, they are not preferred feedstock due to low SSA of the produced biochar. For carbon sequestration, conditions to yield more biochar and rich in carbon contents are desired in order to store greater amount of carbon in soil. Low production temperatures often favor high biochar yield, which implies torrefaction may be the best production process. Whereas, the stability of biochar produced at a low temperature is often poor, which also has high contents of volatile matter. Therefore, therefore, in order to achieve a balance between high yield and stability it is suggested for the future work to assess the effect of biochar stability on potential of carbon retention in soil under different conditions and frames, based on which optimizations of biocarbon production can be done.

Regarding the application in biogas production, alkaline biochar is wanted, which acts as a buffering agent for alleviating ammonia and acids inhibition simultaneously. Large specific surface area and porosity are also important to provide a suitable environment favoring microorganisms colonization, which benefits the yield and quality of biogas. When biochar is used as syntrophic partners, high contents of ash (>50 %), potassium and other trace elements are preferred, which should be considered when selecting feedstock. Therefore, higher temperatures are suggested, which implies that gasification is better than torrefaction and pyrolysis. However, there is little information in the open literature about the impact of temperature on the content of trace elements. Moreover, quantitative effects of properties of biochar such as SSA and pore size distribution on biogas production are lacking. Regarding the feedstock, biochar produced from HB shows higher pH and ash contents than those produced from other feedstock groups; and hence, HB is more suitable for the application in biogas production. Similar to the impact of temperature on trace elements, little work has been done about the impact of feedstock.

Biochar with high SSA and high adsorption capacity can be promising adsorbents for gas cleaning purpose. As shown in Fig. 2, gasification can be the best production process, and WD and HB are the most suitable feedstock. However, gasification results in low yield of biochar. A tradeoff needs to be considered between the SSA and yield to optimize the cost. Furthermore, current studies mainly focus on the removal of NO_x and H_2S. The adsorption capacity of biochar as adsorbent for other pollutants needs more research.

The application of biochar as catalyst is similar to the application for gas cleaning. In addition to specific surface area, surface oxygen functional groups and metal dispersion and speciation are the other two most important properties of biochar need to be considered. Moreover, biochar has a tuneable surface chemistry and porosity that can be engineered to mimic the conventional catalysts. The production temperature in the range of 500–700 °C is revealed as the optimal in terms of specific surface area, porosity and stable polycyclic aromatic carbon. However, with increase of pyrolysis temperature, tarry vapors and volatiles might condensate and block pores.

When using biochar as reductant in metal industry, the typical requirements about FC and VM are higher than 83.6% and in the range of 3.9 -8.75%, respectively [128]. The higher FC and lower VM, the better performance of biochar. As VM decreases while FC increases with rise of production temperature, biochar produced from gasification of WD as feedstock shall be the best.

However, the biochar produced from gasification process has large SSA and porosity, which has high reactivity and density as well. Therefore, slow pyrolysis is still the most widely applied technology for making biochar. When using biochar as fuel, high HHV (>26.5 MJ/kg) is required, which increases with temperature. According to Fig. 6, biochar from HB and WD have comparable energy content. However, the biocarbon from HB biomass materials often has a high content of ash, which has negative influences on energy production process with considering ash related operational problems.

For electrochemical applications, high specific surface areas, pore distribution, high conductivity, high carbon content, low ash content and high N content are the desired properties. It is clear that there are some properties that are affected by temperature in opposite ways, such as SSA and low ash content; while some are not, such as pore distribution. Therefore, as trade-off, pyrolysis is more suitable compared to gasification and torrefaction. According to the requirements on SSA, carbon content, and ash content, WD is the best feedstock, while BS is not recommended. Property modification is also needed to dope N and S on biochar. However, in general, there lacks deep understanding about the quantitative impacts of different properties on the performance. More importantly, little information is available about the impacts of production processes and feedstock on the conductivity of biochar, which is considered as a key property for electrochemical applications.

5. Concluding remarks

This paper aims to provide guidelines and suggestions about how to select the production process and feedstock. In order to achieve the objective, the literature survey was carried out to identify the requirements of different applications on chemical and physical properties of biochar. A larger number of data available in publications are also collected regarding the properties of biochar produced under different conditions and using different feedstock.

Even though different properties have been identified to play key roles in different applications, quantitative analysis about the impacts of properties on application performances is limited. There have been extremely few quantitative field requirements about the properties for applications. It would be of significance if the range of properties could be specified in the future. Meanwhile, although the variation of biochar properties produced from different feedstock with the processing temperature is clear, which follows a certain trend; due to the versatility of biomass, there is still lack of data in order to obtain more accurate functions for property prediction. Moreover, for many properties, high temperatures are always preferable, which nevertheless results in low yields. Comprehensive economic analysis should be carried out to find the optimal production conditions to consider the tradeoff of biochar quality and biochar quantity. In addition, it is also suggested for the future work that the quality of the property data needs to be carefully assessed.

Table 7 Suggestion on feedstock and production process

Applications	Purposes	Suggestion on feedstock	Suggestion on production processes	Knowledge gap
Wastewater treatment	Removal of heavy metal and organic compounds	WD is the preferable feedstock while HB is not recommended	300-400°C and property modification to increase the functional groups	There has been no quantitative comparison about the influences of different functional groups. Less data is available about pH of AW and BS at produced at low temperatures
Soil amendment	To improve fertilizer use efficiency or nutrient use efficiency	HB is the most preferable feedstock, followed by WD	High temperature is recommended, i.e., Gasification > Pyrolysis > Torrefaction	More efforts are needed to understand the stability of biochar. Direct relationship between the stability of biochar and carbon sequestration potential is unclear, which needs to be further explored. Effects of different process parameters, other than pyrolysis severity and properties of biomass feedstock, on stability of biochar. The potential factors to be studied can include purge of different reagents (i.e., CO2 and O2), reactor configuration and operational mode (i.e., batch, semi continuous and continuous) and post treatment of biochar. Optimization of pyrolysis conditions to trade off biochar yield and stability to maximizing content of carbon that can be stored in soil.
	Soil carbon sequestration	WD>HB>AW>BS	Low temperature favors biochar production, i.e. Torrefaction> Pyrolysis > Gasification	
	To improve soil quality	HB>WD>AW>BS	High temperature is recommended, i.e., Gasification > Pyrolysis > Torrefaction	
Biogas production	As buffer and syntrophic partners	HB > BS > AW > WD	Gasification > Pyrolysis > Torrefaction	Little information is available about the impact of temperature on trace elements and the content of potassium and trace elements for different groups of feedstocks. Quantitative effects of properties of biochar such as SSA and pore size distribution on biogas production are also lacking
Gas cleaning	Remove NOx and H_2S	WD > HB> AW >BS	Gasification > Pyrolysis > Torrefaction	Thorough review on properties of biochar produced through gasification is needed, since it has better properties then biochar produced through other technologies to be used for gas cleaning purpose. A tradeoff needs to be considered between the SSA and yield to optimize

				the cost. The adsorption capacity of biochar as adsorbent for other pollutants needs more research. More detailed studies are needed to investigate efficiency of biochar for cleaning gas under those mimicking industrial conditions (i.e., variation of temperaturs and gas compositions).
Catalyst	As Catalyst or catalyst carrier	WD > HB> AW >BS	Gasification > Pyrolysis > Torrefaction. Modification is also needed to increase the functional groups.	Gasification results in low yield of biochar. A trade-off needs to be considered between the SSA and yield.
Metal industry	As reductant and fuel	WD > HB > BS and AW is not recommended	Pyrolysis > Gasification; and biochar production through torrefaction is only recommended for certain biomass feedstocks	More quantitative comparison of biochar with fossil fuel and reductant used in metal production processes are needed. There are great needs to establish reliable and efficient analysis and assessment methods to understand properties and conversion behaviours under temperatures and conditions relevant to industrial processes. The analysis results can be in turn used for modifying and optimizing production process to produce biochar with desired properties.
Electrochemical applications	As electro-catalyst and electrodes	WD is the best feedstock, while BS is not recommended	Pyrolysis is more suitable than gasification and torrefaction.	The influences of key properties have not been quantified due to lack of systematic study with mechanism understanding. Little information is available about the impacts of production processes and feedstock on the conductivity of biochar.

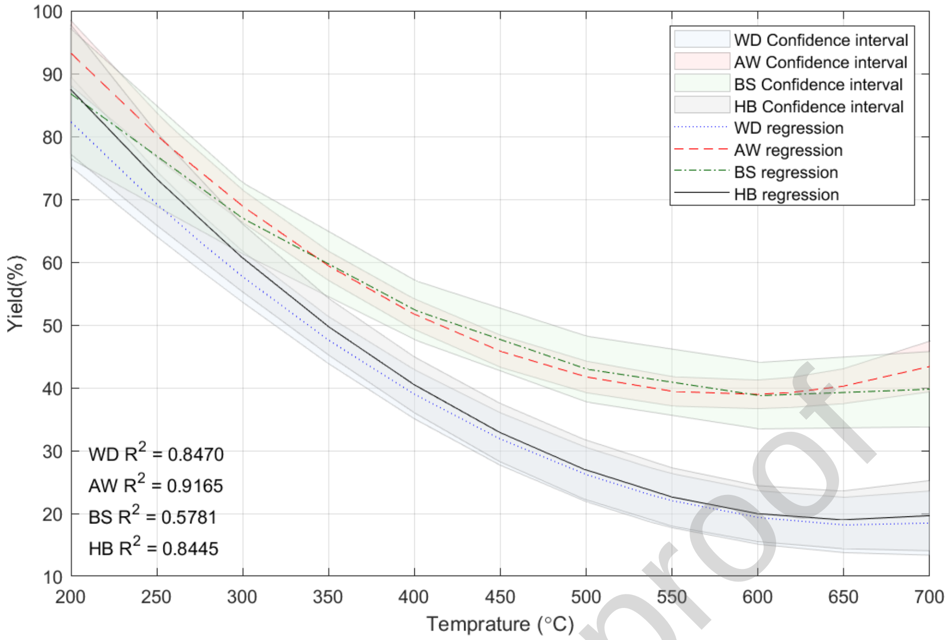


Fig.1 Variation of yield with processing temperature for different feedstock

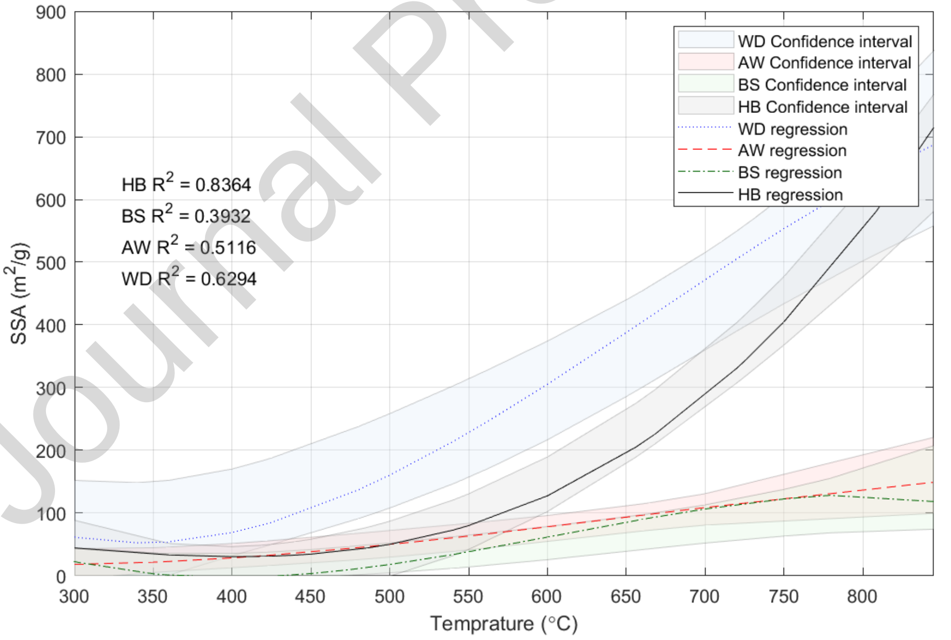


Fig.2 Variation of SSA with processing temperature for different feedstock

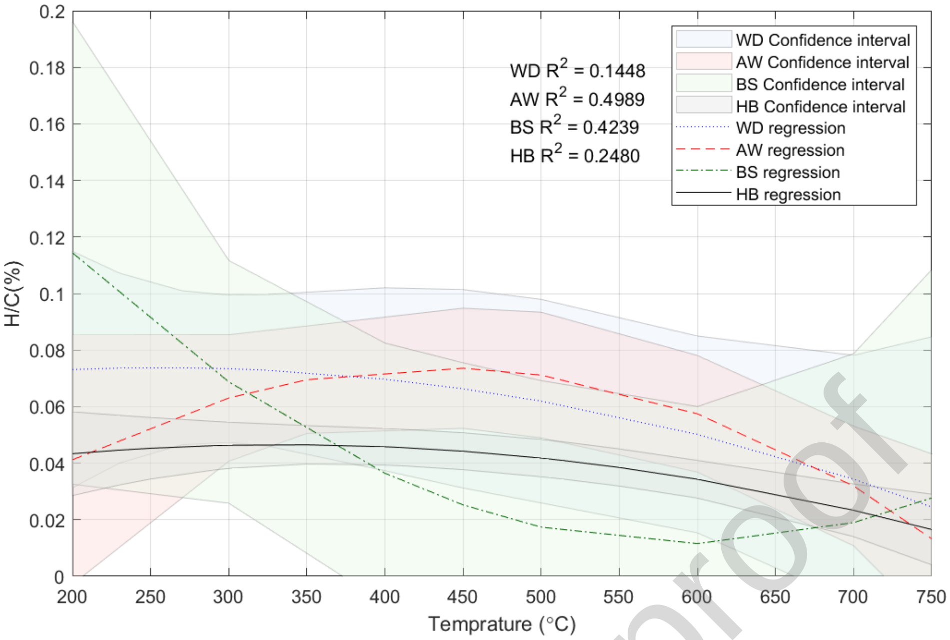


Fig.3 Variation of H/C with processing temperature for different feedstock

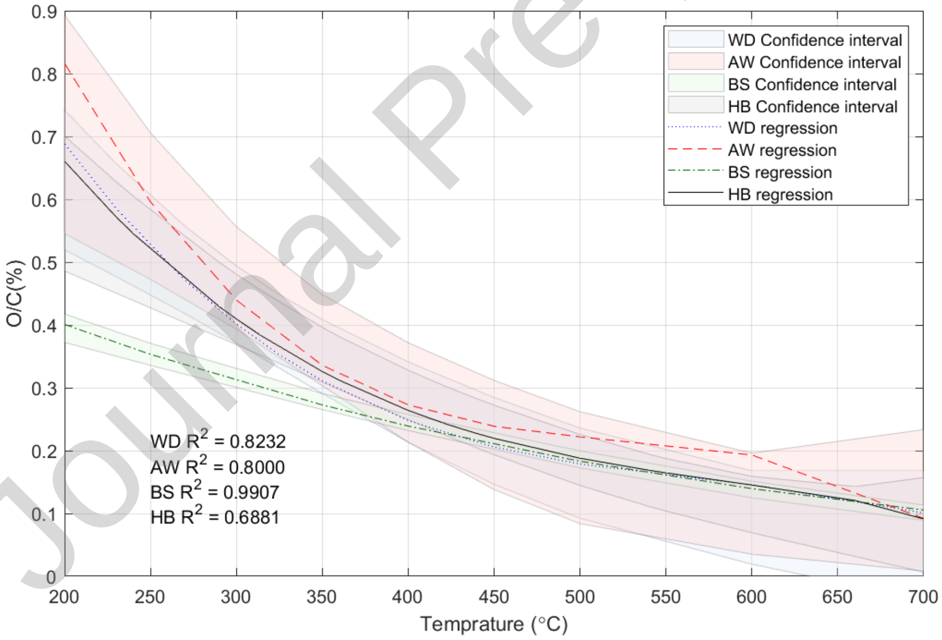


Fig.4 Variation of O/C with processing temperature for different feedstock

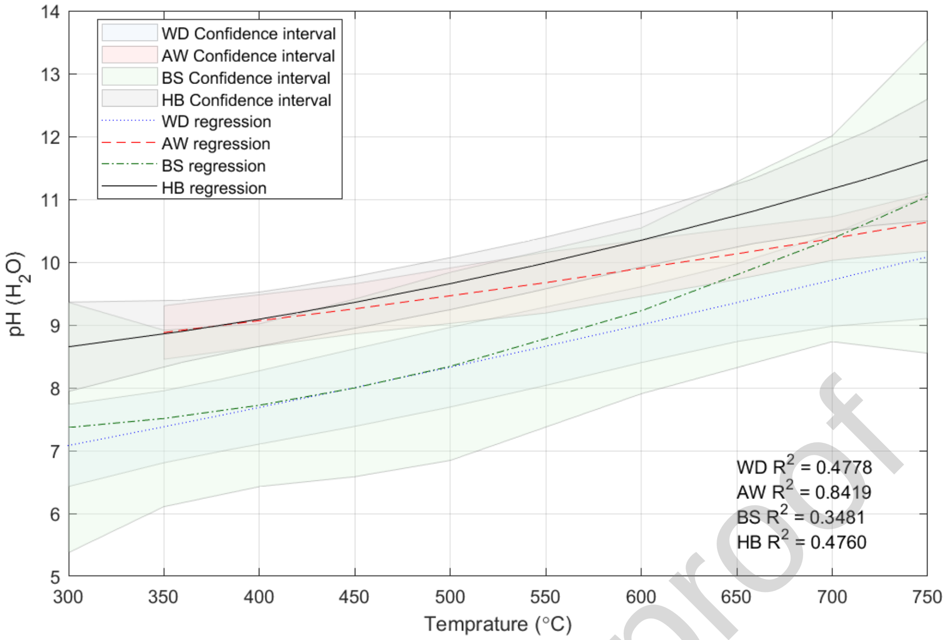


Fig.5 Variation of pH with processing temperature for different feedstock

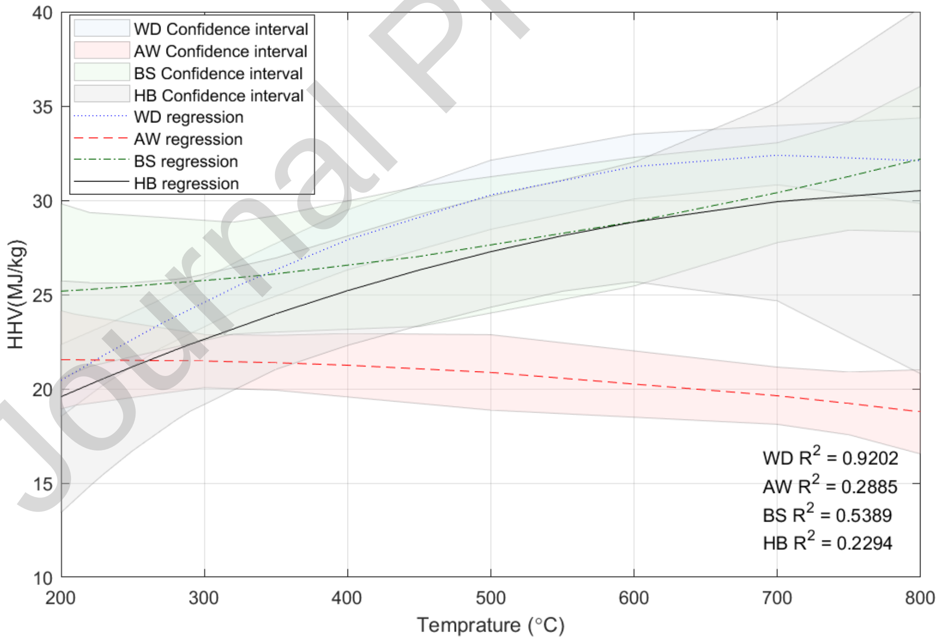
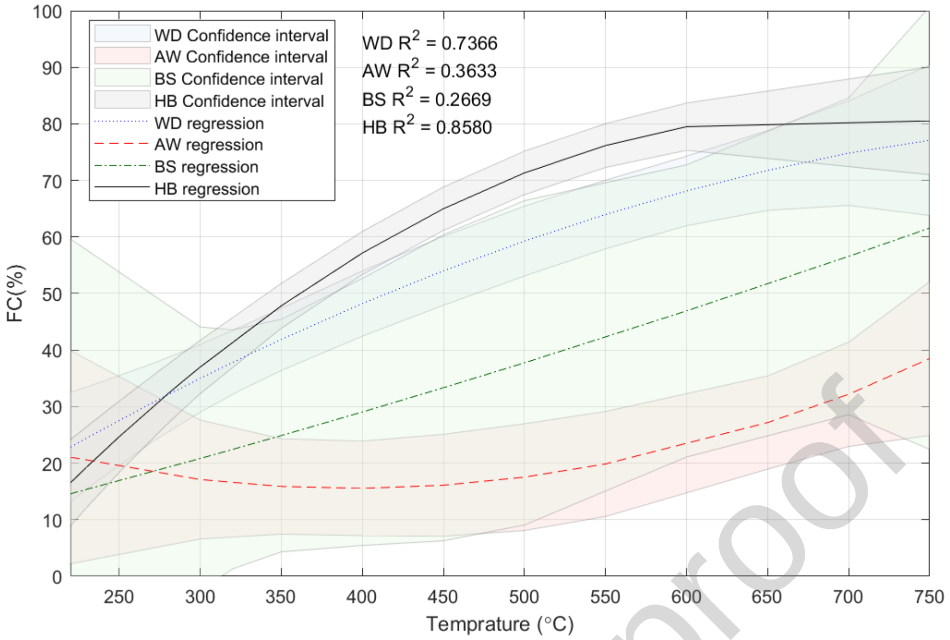
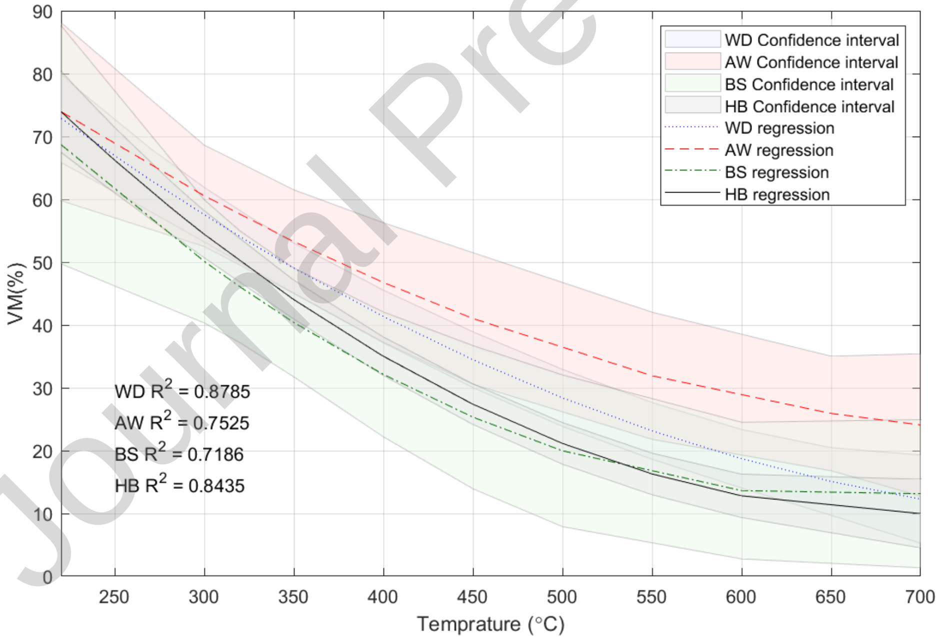


Fig.6 Variation of HHV with processing temperature for different feedstock


100
90
80
70
60
50
40
30
20
10
0
FC(%)
250
300
350
400
450
500
550
600
650
700
750
Temprature (°C)
WD Confidence interval
AW Confidence interval
BS Confidence interval
HB Confidence interval
WD regression
AW regression
BS regression
HB regression
WD R^2 = 0.7366
AW R^2 = 0.3633
BS R^2 = 0.2669
HB R^2 = 0.8580


90
80
70
60
50
40
30
20
10
0
VM(%)
250
300
350
400
450
500
550
600
650
700
Temprature (°C)
WD Confidence interval
AW Confidence interval
BS Confidence interval
HB Confidence interval
WD regression
AW regression
BS regression
HB regression
WD R^2 = 0.8785
AW R^2 = 0.7525
BS R^2 = 0.7186
HB R^2 = 0.8435

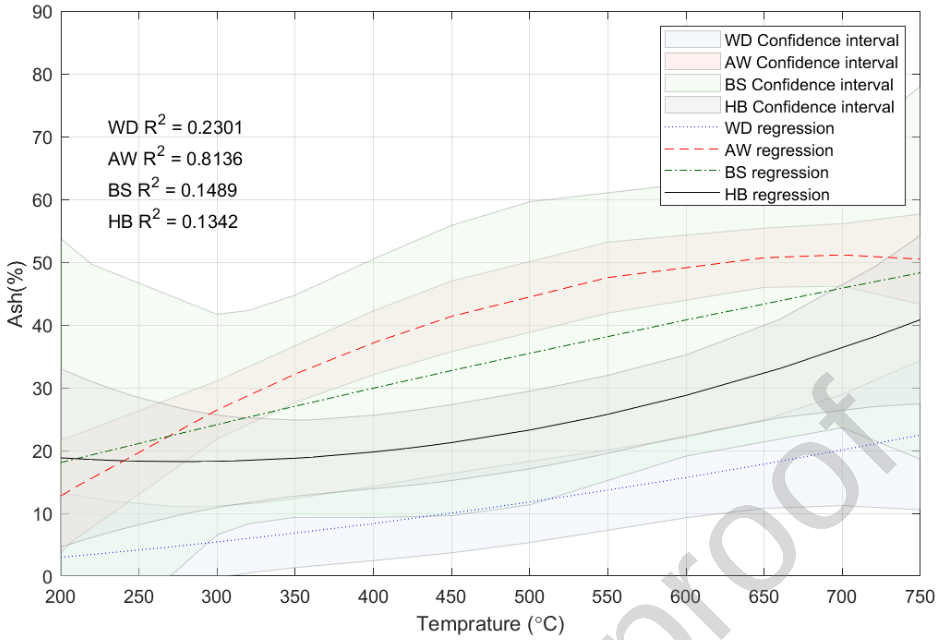


Fig. 7 Proximate properties of biochar change with temperature for different feedstock groups

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References

[1] M. Ahmad, A.U. Rajapaksha, J.E. Lim, M. Zhang, N. Bolan, D. Mohan, M. Vithanage, S.S. Lee, Y.S. Ok, Biochar as a sorbent for contaminant management in soil and water: a review., Chemosphere. 99 (2014) 19–33. https://doi.org/10.1016/j.chemosphere.2013.10.071.

[2] J. Lehmann, S. Joseph, eds., Biochar for environmental management: An introduction, Second edi, International Biochar Initiative, 2009. https://doi.org/10.4324/9781849770552.

[3] Y. Luo, W. Guo, H.H. Ngo, L.D. Nghiem, F.I. Hai, J. Zhang, S. Liang, X.C. Wang, A review on the occurrence of micropollutants in the aquatic environment and their fate and removal during wastewater treatment, Sci. Total Environ. 473–474 (2014) 619–641. https://doi.org/10.1016/j.scitotenv.2013.12.065.

[4] K. Weber, P. Quicker, Properties of biochar, Fuel. 217 (2018) 240–261. https://doi.org/10.1016/j.fuel.2017.12.054.

[5] L. Leng, H. Huang, H. Li, J. Li, W. Zhou, Biochar stability assessment methods: A review, Sci. Total Environ. 647 (2019) 210–222. https://doi.org/10.1016/j.scitotenv.2018.07.402.

[6] S. Li, S. Harris, A. Anandhi, G. Chen, Predicting biochar properties and functions based on feedstock and pyrolysis temperature: A review and data syntheses, J. Clean. Prod. 215 (2019) 890–902. https://doi.org/10.1016/j.jclepro.2019.01.106.

[7] G. Wang, Y. Dai, H. Yang, Q. Xiong, K. Wang, J. Zhou, Y. Li, S. Wang, A review of recent advances in biomass pyrolysis, Energy and Fuels. 34 (2020) 15557–15578. https://doi.org/10.1021/acs.energyfuels.0c03107.

[8] Y. Li, B. Xing, Y. Ding, X. Han, S. Wang, A critical review of the production and advanced utilization of biochar via selective pyrolysis of lignocellulosic biomass, Bioresour. Technol. 312 (2020) 123614. https://doi.org/10.1016/j.biortech.2020.123614.

[9] M.H. Duku, S. Gu, E. Ben Hagan, A comprehensive review of biomass resources and biofuels potential in Ghana, Renew. Sustain. Energy Rev. 15 (2011) 404–415. https://doi.org/10.1016/j.rser.2010.09.033.

[10] W. Wei, P. Mellin, W. Yang, C. Wang, A. Hultgren, H. Salman, Utilization of biomass for blast furnace in Sweden, Stockholm, Sweden, 2013.

[11] T. Xie, K.R. Reddy, C. Wang, E. Yargicoglu, K. Spokas, Characteristics and applications of biochar for environmental remediation: A review, Crit. Rev. Environ. Sci. Technol. 45 (2015) 939–969. https://doi.org/10.1080/10643389.2014.924180.

[12] Q. Liu, F. Yang, Z. hua Liu, G. Li, Preparation of SnO2-Co3O4/C biochar catalyst as a Lewis acid for corncob hydrolysis into furfural in water medium, J. Ind. Eng. Chem. 26 (2015) 46–54. https://doi.org/10.1016/j.jiec.2014.11.041.

[13] M. Tripathi, J.N. Sahu, P. Ganesan, Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review, Renew. Sustain. Energy Rev. 55 (2016) 467–481. https://doi.org/10.1016/j.rser.2015.10.122.

[14] J.S. Cha, S.H. Park, S.C. Jung, C. Ryu, J.K. Jeon, M.C. Shin, Y.K. Park, Production and utilization of biochar: A review, J. Ind. Eng. Chem. 40 (2016) 1–15. https://doi.org/10.1016/j.jiec.2016.06.002.

[15] N.A. Qambrani, M.M. Rahman, S. Won, S. Shim, C. Ra, Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: A review, Renew. Sustain. Energy Rev. 79 (2017) 255–273. https://doi.org/10.1016/j.rser.2017.05.057.

[16] K.R. Thines, E.C. Abdullah, N.M. Mubarak, M. Ruthiraan, Synthesis of magnetic biochar from agricultural waste biomass to enhancing route for waste water and polymer application: A review, Renew. Sustain. Energy Rev. 67 (2017) 257–276. https://doi.org/10.1016/j.rser.2016.09.057.

[17] B. Sajjadi, W.Y. Chen, N.O. Egiebor, Chemical activation of biochar for energy and environmental applications: a comprehensive review, Rev. Chem. Eng. (2018) 1–39. https://doi.org/10.1515/revce-2017-0113.

[18] J.M.C. Ribeiro, R. Godina, J.C. de O. Matias, L.J.R. Nunes, Future perspectives of biomass torrefaction: Review of the current state-of-the-art and research development, Sustainability. 10 (2018) 1–17. https://doi.org/10.3390/su10072323.

[19] O.A. Akogun, M.A. Waheed, Property Upgrades of Some Raw Nigerian Biomass through Torrefaction Pre-Treatment- A Review, J. Phys. Conf. Ser. 1378 (2019). https://doi.org/10.1088/1742-6596/1378/3/032026.

[20] S. Barskov, M. Zappi, P. Buchireddy, S. Dufreche, J. Guillory, D. Gang, R. Hernandez, R. Bajpai, J. Baudier, R. Cooper, R. Sharp, Torrefaction of biomass: A review of production methods for biocoal from cultured and waste lignocellulosic feedstocks, Renew. Energy. 142 (2019) 624–642. https://doi.org/10.1016/j.renene.2019.04.068.

[21] K.S.D. Premarathna, A.U. Rajapaksha, B. Sarkar, E.E. Kwon, A. Bhatnagar, Y.S. Ok, M. Vithanage, Biochar-based engineered composites for sorptive decontamination of water: A review, Chem. Eng. J. 372 (2019) 536–550. https://doi.org/10.1016/j.cej.2019.04.097.

[22] A. Tursi, A review on biomass: Importance, chemistry, classification, and conversion, Biofuel Res. J. 6 (2019) 962–979. https://doi.org/10.18331/BRJ2019.6.2.3.

[23] S. Sohi, E. Lopez-capel, E. Krull, R. Bol, Biochar , climate change and soil : A review to guide future research, 2009. https://doi.org/10.1139/Z03-132.

[24] M.I. Inyang, B. Gao, Y. Yao, Y. Xue, A. Zimmerman, A. Mosa, P. Pullammanappallil, Y.S. Ok, X. Cao, A review of biochar as a low-cost adsorbent for aqueous heavy metal removal, Crit. Rev. Environ. Sci. Technol. 46 (2016) 406–433. https://doi.org/10.1080/10643389.2015.1096880.

[25] J. Lehmann, M.C. Rillig, J. Thies, C.A. Masiello, W.C. Hockaday, D. Crowley, Biochar effects on soil biota - A review, Soil Biol. Biochem. 43 (2011) 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022.

[26] J.J. Manyà, Pyrolysis for biochar purposes: A review to establish current knowledge gaps and research needs, Environ. Sci. Technol. 46 (2012) 7939–7954. https://doi.org/10.1021/es301029g.

[27] N. Ameloot, E.R. Graber, F.G.A. Verheijen, S. De Neve, Interactions between biochar stability and soil organisms: Review and research needs, Eur. J. Soil Sci. 64 (2013) 379–390. https://doi.org/10.1111/ejss.12064.

[28] M. Inyang, E. Dickenson, The potential role of biochar in the removal of organic and microbial contaminants from potable and reuse water: A review, Chemosphere. 134 (2015) 232–240. https://doi.org/10.1016/j.chemosphere.2015.03.072.

[29] A.H. Lone, G.R. Najar, M.A. Ganie, J.A. Sofi, T. Ali, Biochar for Sustainable Soil Health: A Review of Prospects and Concerns, Pedosphere. 25 (2015) 639–653. https://doi.org/10.1016/S1002-0160(15)30045-X.

[30] Y. Dai, N. Zhang, C. Xing, Q. Cui, Q. Sun, The adsorption, regeneration and engineering applications of biochar for removal organic pollutants: A review, Chemosphere. 223 (2019) 12–27. https://doi.org/10.1016/j.chemosphere.2019.01.161.

[31] X. Tan, Y. Liu, Y. Gu, Y. Xu, G. Zeng, X. Hu, S. Liu, X. Wang, S. Liu, J. Li, Biochar-based nano-composites for the decontamination of wastewater: A review, Bioresour. Technol. 212 (2016) 318–333. https://doi.org/10.1016/j.biortech.2016.04.093.

[32] X. Cao, S. Sun, R. Sun, Application of biochar-based catalysts in biomass upgrading: A review, RSC Adv. 7 (2017) 48793–48805. https://doi.org/10.1039/c7ra09307a.

[33] W. Gwenzi, N. Chaukura, C. Noubactep, F.N.D. Mukome, Biochar-based water treatment systems as a potential low-cost and sustainable technology for clean water provision, J. Environ. Manage. 197 (2017) 732–749. https://doi.org/10.1016/j.jenvman.2017.03.087.

[34] J. Lee, K.H. Kim, E.E. Kwon, Biochar as a Catalyst, Renew. Sustain. Energy Rev. 77 (2017) 70–79. https://doi.org/10.1016/j.rser.2017.04.002.

[35] F.R. Oliveira, A.K. Patel, D.P. Jaisi, S. Adhikari, H. Lu, S.K. Khanal, Environmental application of biochar: Current status and perspectives, Bioresour. Technol. 246 (2017) 110–122. https://doi.org/10.1016/j.biortech.2017.08.122.

[36] S. Xiu, A. Shahbazi, R. Li, Characterization, Modification and Application of Biochar for Energy Storage and Catalysis: A Review, Trends Renew. Energy. 3 (2017) 86–101. https://doi.org/10.17737/tre.2017.3.1.0033.

[37] Z. Tan, C.S.K. Lin, X. Ji, T.J. Rainey, Returning biochar to fields: A review, Appl. Soil Ecol. 116 (2017) 1–11. https://doi.org/10.1016/j.apsoil.2017.03.017.

[38] M.I. Al-Wabel, Q. Hussain, A.R.A. Usman, M. Ahmad, A. Abduljabbar, A.S. Sallam, Y.S. Ok, Impact of biochar properties on soil conditions and agricultural sustainability: A review, L. Degrad. Dev. (2017) 1–38. https://doi.org/10.1002/ldr.2829.

[39] F. Codignole Luz, S. Cordiner, A. Manni, V. Mulone, V. Rocco, Biochar characteristics and early applications in anaerobic digestion-a review, J. Environ. Chem. Eng. 6 (2018) 2892–2909. https://doi.org/10.1016/j.jece.2018.04.015.

[40] Z. Liu, S. Singer, Y. Tong, L. Kimbell, E. Anderson, M. Hughes, D. Zitomer, P. McNamara, Characteristics and applications of biochars derived from wastewater solids, Renew. Sustain. Energy Rev. 90 (2018) 650–664. https://doi.org/10.1016/j.rser.2018.02.040.

[41] L. Li, D. Zou, Z. Xiao, X. Zeng, L. Zhang, L. Jiang, A. Wang, D. Ge, G. Zhang, F. Liu, Biochar as a sorbent for emerging contaminants enables improvements in waste management and sustainable resource use, J. Clean. Prod. 210 (2019) 1324–1342. https://doi.org/10.1016/j.jclepro.2018.11.087.

[42] S.O. Masebinu, E.T. Akinlabi, E. Muzenda, A.O. Aboyade, A review of biochar properties and their roles in mitigating challenges with anaerobic digestion, Renew. Sustain. Energy Rev. 103 (2019) 291–307. https://doi.org/10.1016/j.rser.2018.12.048.

[43] L. Qiu, Y.F. Deng, F. Wang, M. Davaritouchaee, Y.Q. Yao, A review on biochar-mediated anaerobic digestion with enhanced methane recovery, Renew. Sustain. Energy Rev. 115 (2019) 109373. https://doi.org/10.1016/j.rser.2019.109373.

[44] J. Wang, S. Wang, Preparation, modification and environmental application of biochar: A review, J. Clean. Prod. 227 (2019) 1002–1022. https://doi.org/10.1016/j.jclepro.2019.04.282.

[45] T.J. Purakayastha, T. Bera, D. Bhaduri, B. Sarkar, S. Mandal, P. Wade, S. Kumari, S. Biswas, M. Menon, H. Pathak, D.C.W. Tsang, A review on biochar modulated soil condition improvements and nutrient dynamics concerning crop yields: Pathways to climate change mitigation and global food security, Chemosphere. 227 (2019) 345–365. https://doi.org/10.1016/j.chemosphere.2019.03.170.

[46] K. Kalus, J.A. Koziel, S. Opaliński, A review of biochar properties and their utilization in crop agriculture and livestock production, Appl. Sci. 9 (2019) 1–16. https://doi.org/10.3390/app9173494.

[47] M.Z. Rahman, T. Edvinsson, P. Kwong, Biochar for electrochemical applications, Curr. Opin. Green Sustain. Chem. 23 (2020) 25–30. https://doi.org/10.1016/j.cogsc.2020.04.007.

[48] J.A. Antonangelo, X. Sun, H. Zhang, The roles of co-composted biochar (COMBI) in improving soil quality, crop productivity, and toxic metal amelioration, J. Environ. Manage. 277 (2021) 1–13. https://doi.org/10.1016/j.jenvman.2020.111443.

[49] Y. Ding, Y. Liu, S. Liu, Z. Li, X. Tan, X. Huang, G. Zeng, L. Zhou, B. Zheng, Biochar to improve soil fertility. A review, Agron. Sustain. Dev. 36 (2016). https://doi.org/10.1007/s13593-016-0372-z.

[50] S. Sri Shalini, K. Palanivelu, A. Ramachandran, V. Raghavan, Biochar from biomass waste as

a renewable carbon material for climate change mitigation in reducing greenhouse gas emissions—a review, Biomass Convers. Biorefinery. 280 (2020). https://doi.org/10.1007/s13399-020-00604-5.

[51] X. Tan, Y. Liu, G. Zeng, X. Wang, X. Hu, Y. Gu, Z. Yang, Application of biochar for the removal of pollutants from aqueous solutions, Chemosphere. 125 (2015) 70–85. https://doi.org/10.1016/j.chemosphere.2014.12.058.

[52] L.K. Kimbell, Y. Tong, B.K. Mayer, P.J. McNamara, Biosolids-Derived Biochar for Triclosan Removal from Wastewater, Environ. Eng. Sci. 35 (2018) 513–524. https://doi.org/10.1089/ees.2017.0291.

[53] S. Sajjadi, A. Mohammadzadeh, H.N. Tran, I. Anastopoulos, G.L. Dotto, Z.R. Lopičić, S. Sivamani, A. Rahmani-Sani, A. Ivanets, A. Hosseini-Bandegharaei, Efficient mercury removal from wastewater by pistachio wood wastes-derived activated carbon prepared by chemical activation using a novel activating agent, J. Environ. Manage. 223 (2018) 1001–1009. https://doi.org/10.1016/j.jenvman.2018.06.077.

[54] C. Tan, Z. Zhou, R. Han, R. Meng, H. Wang, W. Lu, Adsorption of cadmium by biochar derived from municipal sewage sludge: Impact factors and adsorption mechanism, Chemosphere. 134 (2015) 286–293. https://doi.org/10.1016/j.chemosphere.2015.04.052.

[55] H. Li, X. Dong, E.B. da Silva, L.M. de Oliveira, Y. Chen, L.Q. Ma, Mechanisms of metal sorption by biochars: Biochar characteristics and modifications, Chemosphere. 178 (2017) 466–478. https://doi.org/10.1016/j.chemosphere.2017.03.072.

[56] A.W. Samsuri, F. Sadegh-Zadeh, B.J. Seh-Bardan, Characterization of biochars produced from oil palm and rice husks and their adsorption capacities for heavy metals, Int. J. Environ. Sci. Technol. 11 (2014) 967–976. https://doi.org/10.1007/s13762-013-0291-3.

[57] J.M. Patra, S.S. Panda, N.K. Dhal, Biochar as a low-cost adsorbent for heavy metal removal: A review, Int. J. Res. Biosci. 6 (2017) 1–7. http://www.ijrbs.in.

[58] M. Inyang, B. Gao, P. Pullammanappallil, W. Ding, A.R. Zimmerman, Biochar from anaerobically digested sugarcane bagasse, Bioresour. Technol. 101 (2010) 8868–8872. https://doi.org/10.1016/j.biortech.2010.06.088.

[59] P. De Rozari, M. Greenway, A. El Hanandeh, An investigation into the effectiveness of sand media amended with biochar to remove BOD5, suspended solids and coliforms using wetland mesocosms, Water Sci. Technol. 71 (2015) 1536–1544. https://doi.org/10.2166/wst.2015.120.

[60] P. de Rozari, M. Greenway, A. El Hanandeh, Phosphorus removal from secondary sewage and septage using sand media amended with biochar in constructed wetland mesocosms, Sci. Total Environ. 569–570 (2016) 123–133. https://doi.org/10.1016/j.scitotenv.2016.06.096.

[61] P. de Rozari, M. Greenway, A. El Hanandeh, Nitrogen removal from sewage and septage in constructed wetland mesocosms using sand media amended with biochar, Ecol. Eng. 111 (2018) 1–10. https://doi.org/10.1016/j.ecoleng.2017.11.002.

[62] A. Beckinghausen, J. Reynders, R. Merckel, Y.W. Wu, H. Marais, S. Schwede, Post-pyrolysis treatments of biochars from sewage sludge and A. mearnsii for ammonia (NH4-n) recovery, Appl. Energy. 271 (2020) 115212. https://doi.org/10.1016/j.apenergy.2020.115212.

[63] T.M. Huggins, A. Haeger, J.C. Biffinger, Z.J. Ren, Granular biochar compared with activated carbon for wastewater treatment and resource recovery, Water Res. 94 (2016) 225–232. https://doi.org/10.1016/j.watres.2016.02.059.

[64] P. Gupta, T.W. Ann, S.M. Lee, Use of biochar to enhance constructed wetland performance in wastewater reclamation, Environ. Eng. Res. 21 (2016) 36–44. https://doi.org/10.4491/eer.2015.067.

[65] J. Zhou, S. Liu, N. Zhou, L. Fan, Y. Zhang, P. Peng, E. Anderson, K. Ding, Y. Wang, Y. Liu, P. Chen, R. Ruan, Development and application of a continuous fast microwave pyrolysis system for sewage sludge utilization, Bioresour. Technol. 256 (2018) 295–301. https://doi.org/10.1016/j.biortech.2018.02.034.

[66] K. Nobaharan, S.B. Novair, B.A. Lajayer, E.D. Van Hullebusch, Phosphorus removal from wastewater: The potential use of biochar and the key controlling factors, Water (Switzerland).

13 (2021) 1–20. https://doi.org/10.3390/w13040.

[67] E. Rosales, J. Meijide, M. Pazos, M.A. Sanromán, Challenges and recent advances in biochar as low-cost biosorbent: From batch assays to continuous-flow systems, Bioresour. Technol. 246 (2017) 176–192. https://doi.org/10.1016/j.biortech.2017.06.084.

[68] D. Mohan, A. Sarswat, Y.S. Ok, C.U. Pittman, Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent - A critical review, Bioresour. Technol. 160 (2014) 191–202. https://doi.org/10.1016/j.biortech.2014.01.120.

[69] A.U. Rajapaksha, M. Vithanage, S.S. Lee, D.C. Seo, D.C.W. Tsang, Y.S. Ok, Steam activation of biochars facilitates kinetics and pH-resilience of sulfamethazine sorption, J. Soils Sediments. 16 (2016) 889–895. https://doi.org/10.1007/s11368-015-1325-x.

[70] M.B. Ahmed, J.L. Zhou, H.H. Ngo, W. Guo, M.A.H. Johir, K. Sornalingam, Single and competitive sorption properties and mechanism of functionalized biochar for removing sulfonamide antibiotics from water, Chem. Eng. J. 311 (2017) 348–358. https://doi.org/10.1016/j.cej.2016.11.106.

[71] T.G. Ambaye, M. Vaccari, E.D. van Hullebusch, A. Amrane, S. Rtimi, Mechanisms and adsorption capacities of biochar for the removal of organic and inorganic pollutants from industrial wastewater, Int. J. Environ. Sci. Technol. (2020). https://doi.org/10.1007/s13762-020-03060-w.

[72] M. Uchimiya, L.H. Wartelle, I.M. Lima, K.T. Klasson, Sorption of deisopropylatrazine on broiler litter biochars, J. Agric. Food Chem. 58 (2010) 12350–12356. https://doi.org/10.1021/jf102152q.

[73] M. Ahmad, S.S. Lee, X. Dou, D. Mohan, J.K. Sung, J.E. Yang, Y.S. Ok, Effects of pyrolysis temperature on soybean stover- and peanut shell-derived biochar properties and TCE adsorption in water, Bioresour. Technol. 118 (2012) 536–544. https://doi.org/10.1016/j.biortech.2012.05.042.

[74] A. Budai, L. Wang, M. Gronli, T.S. Strand, M.J. Antal, S. Abiven, A. Dieguez-Alonso, A. Anca-Couse, D.P. Rasse, Surface Properties and Chemical Composition of Corncob and Miscanthus Biochars : Effects of Production Temperature .... Surface Properties and Chemical Composition of Corncob and Miscanthus Biochars : Effects of Production Temperature and Method, J. Agric. Food Chem. 62 (2014) 3791–3799. https://doi.org/10.1080/10426910802679196.

[75] S.E. Hale, H.P.H. Arp, D. Kupryianchyk, G. Cornelissen, A synthesis of parameters related to the binding of neutral organic compounds to charcoal, Chemosphere. 144 (2016) 65–74. https://doi.org/10.1016/j.chemosphere.2015.08.047.

[76] J.G. Shang, X.R. Kong, L.L. He, W.H. Li, Q.J.H. Liao, Low-cost biochar derived from herbal residue: characterization and application for ciprofloxacin adsorption, Int. J. Environ. Sci. Technol. 13 (2016) 2449–2458. https://doi.org/10.1007/s13762-016-1075-3.

[77] M. Essandoh, B. Kunwar, C.U. Pittman, D. Mohan, T. Mlsna, Sorptive removal of salicylic acid and ibuprofen from aqueous solutions using pine wood fast pyrolysis biochar, Chem. Eng. J. 265 (2015) 219–227. https://doi.org/10.1016/j.cej.2014.12.006.

[78] Y. Jayawardhana, P. Kumarathilaka, S. Mayakaduwa, L. Weerasundara, T. Bandara, M. Vithanage, Characteristics of municipal solid waste biochar: Its potential to be used in environmental remediation, in: S. Ghosh (Ed.), Util. Manag. Bioresour., Springer, Singapore, 2018. https://doi.org/10.1007/978-981-10-5349-8.

[79] R. kou Xu, S. cheng Xiao, J. hua Yuan, A. zhen Zhao, Adsorption of methyl violet from aqueous solutions by the biochars derived from crop residues, Bioresour. Technol. 102 (2011) 10293–10298. https://doi.org/10.1016/j.biortech.2011.08.089.

[80] H. Bier, H. Gerber, M. Huber, H. Junginger, D. Kray, J. Lange, H. Lerchenmüller, P.J. Nilsen, Biochar-based carbon sinks to mitigate climate change, Eur. Biochar Ind. Consort. (2020). http://www.biochar-industry.com/.

[81] X. Yu, L. Pan, G. Ying, R.S. Kookana, Enhanced and irreversible sorption of pesticide pyrimethanil by soil amended with biochars, J. Environ. Sci. 22 (2010) 615–620.

https://doi.org/10.1016/S1001-0742(09)60153-4.

[82] M. Olmo, R. Villar, P. Salazar, J.A. Alburquerque, Changes in soil nutrient availability explain biochar's impact on wheat root development, Plant Soil. 399 (2016) 333–343. https://doi.org/10.1007/s11104-015-2700-5.

[83] A. El-Naggar, S.S. Lee, J. Rinklebe, M. Farooq, H. Song, A.K. Sarmah, A.R. Zimmerman, M. Ahmad, S.M. Shaheen, Y.S. Ok, Biochar application to low fertility soils: A review of current status, and future prospects, Geoderma. 337 (2019) 536–554. https://doi.org/10.1016/j.geoderma.2018.09.034.

[84] M. Laghari, M.S. Mirjat, Z. Hu, S. Fazal, B. Xiao, M. Hu, Z. Chen, D. Guo, Effects of biochar application rate on sandy desert soil properties and sorghum growth, Catena. 135 (2015) 313–320. https://doi.org/10.1016/j.catena.2015.08.013.

[85] K.A. Spokas, J.M. Novak, R.T. Venterea, Biochar's role as an alternative N-fertilizer: Ammonia capture, Plant Soil. 350 (2012) 35–42. https://doi.org/10.1007/s11104-011-0930-8.

[86] Y. Lin, P. Munroe, S. Joseph, R. Henderson, A. Ziolkowski, Water extractable organic carbon in untreated and chemical treated biochars, Chemosphere. 87 (2012) 151–157. https://doi.org/10.1016/j.chemosphere.2011.12.007.

[87] D. Laird, P. Fleming, B. Wang, R. Horton, D. Karlen, Biochar impact on nutrient leaching from a Midwestern agricultural soil, Geoderma. 158 (2010) 436–442. https://doi.org/10.1016/j.geoderma.2010.05.012.

[88] X. Liu, A. Zhang, C. Ji, S. Joseph, R. Bian, L. Li, G. Pan, J. Paz-Ferreiro, Biochar's effect on crop productivity and the dependence on experimental conditions-a meta-analysis of literature data, Plant Soil. 373 (2013) 583–594. https://doi.org/10.1007/s11104-013-1806-x.

[89] J. Ishii, F. Okazaki, A.C. Djohan, K.Y. Hara, N. Asai-Nakashima, H. Teramura, A. Andriani, M. Tominaga, S. Wakai, P. Kahar, Yopi, B. Prasetya, C. Ogino, A. Kondo, From mannan to bioethanol: Cell surface co-display of β-mannanase and β-mannosidase on yeast Saccharomyces cerevisiae, Biotechnol. Biofuels. 9 (2016) 1–15. https://doi.org/10.1186/s13068-016-0600-4.

[90] B. Arias, C. Pevida, J. Fermoso, M.G. Plaza, F. Rubiera, J.J. Pis, Influence of torrefaction on the grindability and reactivity of woody biomass, Fuel Process. Technol. 89 (2008) 169–175. https://doi.org/10.1016/j.fuproc.2007.09.002.

[91] X. Zhao, W. Ouyang, F. Hao, C. Lin, F. Wang, S. Han, X. Geng, Properties comparison of biochars from corn straw with different pretreatment and sorption behaviour of atrazine, Bioresour. Technol. 147 (2013) 338–344. https://doi.org/10.1016/j.biortech.2013.08.042.

[92] H. Schmidt, B. Pandit, V. Martinsen, G. Cornelissen, P. Conte, C. Kammann, Fourfold Increase in Pumpkin Yield in Response to Low-Dosage Root Zone Application of Urine-Enhanced Biochar to a Fertile Tropical Soil, Agriculture. 5 (2015) 723–741. https://doi.org/10.3390/agriculture5030723.

[93] Z. Dai, X. Zhang, C. Tang, N. Muhammad, J. Wu, P.C. Brookes, J. Xu, Potential role of biochars in decreasing soil acidification - A critical review, Sci. Total Environ. 581–582 (2017) 601–611. https://doi.org/10.1016/j.scitotenv.2016.12.169.

[94] A. Mukherjee, A.R. Zimmerman, W. Harris, Surface chemistry variations among a series of laboratory-produced biochars, Geoderma. 163 (2011) 247–255. https://doi.org/10.1016/j.geoderma.2011.04.021.

[95] Y. Sung, M. Li, D. Luo, Y. Li, S. Biring, Y. Huang, C. Wang, S. Liu, K. Wong, A crical review on performance indicators for evaluating soil biota and soil health of biochar-amended soils, J. Hazard. Mater. (2020) 105565. https://doi.org/10.1016/j.jhazmat.2021.125378.

[96] Z. Shen, Y. Zhang, O. McMillan, D. O'Connor, D. Hou, Chapter 6 - The use of biochar for sustainable treatment of contaminated soils, Elsevier Inc., 2020. https://doi.org/10.1016/b978-0-12-817982-6.00006-9.

[97] M. Wang, J.J. Wang, X. Wang, Effect of KOH-enhanced biochar on increasing soil plant-available silicon, Geoderma. 321 (2018) 22–31. https://doi.org/10.1016/j.geoderma.2018.02.001.

[98] D. O’Connor, T. Peng, G. Li, S. Wang, L. Duan, J. Mulder, G. Cornelissen, Z. Cheng, S. Yang, D. Hou, Sulfur-modified rice husk biochar: A green method for the remediation of mercury contaminated soil, Sci. Total Environ. 621 (2018) 819–826. https://doi.org/10.1016/j.scitotenv.2017.11.213.

[99] M. Uchimiya, S.C. Chang, K.T. Klasson, Screening biochars for heavy metal retention in soil: Role of oxygen functional groups, J. Hazard. Mater. 190 (2011) 432–441. https://doi.org/10.1016/j.jhazmat.2011.03.063.

[100] Z. Shen, Y. Zhang, O. McMillan, F. Jin, A. Al-Tabbaa, Characteristics and mechanisms of nickel adsorption on biochars produced from wheat straw pellets and rice husk, Environ. Sci. Pollut. Res. 24 (2017) 12809–12819. https://doi.org/10.1007/s11356-017-8847-2.

[101] J.H. Yuan, R.K. Xu, N. Wang, J.Y. Li, Amendment of Acid Soils with Crop Residues and Biochars, Pedosphere. 21 (2011) 302–308. https://doi.org/10.1016/S1002-0160(11)60130-6.

[102] M. Safaei Khorram, Q. Zhang, D. Lin, Y. Zheng, H. Fang, Y. Yu, Biochar: A review of its impact on pesticide behavior in soil environments and its potential applications, J. Environ. Sci. (China). 44 (2016) 269–279. https://doi.org/10.1016/j.jes.2015.12.027.

[103] F. Sopeña, K. Semple, S. Sohi, G. Bending, Assessing the chemical and biological accessibility of the herbicide isoproturon in soil amended with biochar, Chemosphere. 88 (2012) 77–83. https://doi.org/10.1016/j.chemosphere.2012.02.066.

[104] A. Cabrera, L. Cox, K. Spokas, M.C. Hermosín, J. Cornejo, W.C. Koskinen, Influence of biochar amendments on the sorption-desorption of aminocyclopyrachlor, bentazone and pyraclostrobin pesticides to an agricultural soil, Sci. Total Environ. 470–471 (2014) 438–443. https://doi.org/10.1016/j.scitotenv.2013.09.080.

[105] D.L. Jones, G. Edwards-Jones, D. V. Murphy, Biochar mediated alterations in herbicide breakdown and leaching in soil, Soil Biol. Biochem. 43 (2011) 804–813. https://doi.org/10.1016/j.soilbio.2010.12.015.

[106] X.Y. Yu, G.G. Ying, R.S. Kookana, Reduced plant uptake of pesticides with biochar additions to soil, Chemosphere. 76 (2009) 665–671. https://doi.org/10.1016/j.chemosphere.2009.04.001.

[107] T.T. Wang, J. Cheng, X.J. Liu, W. Jiang, C.L. Zhang, X.Y. Yu, Effect of biochar amendment on the bioavailability of pesticide chlorantraniliprole in soil to earthworm, Ecotoxicol. Environ. Saf. 83 (2012) 96–101. https://doi.org/10.1016/j.ecoenv.2012.06.012.

[108] X.B. Yang, G.G. Ying, P.A. Peng, L. Wang, J.L. Zhao, L.J. Zhang, P. Yuan, H.P. He, Influence of biochars on plant uptake and dissipation of two pesticides in an agricultural soil, J. Agric. Food Chem. 58 (2010) 7915–7921. https://doi.org/10.1021/jf1011352.

[109] D. O’Connor, T. Peng, J. Zhang, D.C.W. Tsang, D.S. Alessi, Z. Shen, N.S. Bolan, D. Hou, Biochar application for the remediation of heavy metal polluted land: A review of in situ field trials, Sci. Total Environ. 619–620 (2018) 815–826. https://doi.org/10.1016/j.scitotenv.2017.11.132.

[110] C.J. Barrow, Biochar: Potential for countering land degradation and for improving agriculture, Appl. Geogr. 34 (2012) 21–28. https://doi.org/10.1016/j.apgeog.2011.09.008.

[111] L. Wang, Ø. Skreiberg, M. Gronli, G.P. Specht, M.J. Antal, Is elevated pressure required to achieve a high fixed-carbon yield of charcoal from biomass? Part 2: The importance of particle size, Energy and Fuels. 27 (2013) 2146–2156. https://doi.org/10.1021/ef400041h.

[112] K. Crombie, O. Mašek, S.P. Sohi, P. Brownsort, A. Cross, The effect of pyrolysis conditions on biochar stability as determined by three methods, GCB Bioenergy. 5 (2013) 122–131. https://doi.org/10.1111/gcbb.12030.

[113] M. Keiluweit, P.S. Nico, M.G. Johnson, M. KLEBER, Dynamic Molecular Structure of Plant Biomass-derived Black Carbon(Biochar)- Supporting Information -, Environ. Sci. Technol. 44 (2010) 1247–1253. 10.1021/es9031419.

[114] A. V Mcbeath, R.J. Smernik, M.P.W. Schneider, M.W.I. Schmidt, E.L. Plant, Determination of the aromaticity and the degree of aromatic condensation of a thermosequence of wood charcoal using NMR, Org. Geochem. 42 (2011) 1194–1202. https://doi.org/10.1016/j.orggeochem.2011.08.008.

[115] A. V. McBeath, R.J. Smernik, E.S. Krull, J. Lehmann, The influence of feedstock and production temperature on biochar carbon chemistry: A solid-state 13C NMR study, Biomass and Bioenergy. 60 (2014) 121–129. https://doi.org/10.1016/j.biombioe.2013.11.002.

[116] E. Barta-Rajnai, E. Jakab, Z. Sebestyén, Z. May, Z. Barta, L. Wang, Ø. Skreiberg, M. Grønli, J. Bozi, Z. Czégény, Comprehensive Compositional Study of Torrefied Wood and Herbaceous Materials by Chemical Analysis and Thermoanalytical Methods, Energy and Fuels. 30 (2016) 8019–8030. https://doi.org/10.1021/acs.energyfuels.6b01030.

[117] K.A. Spokas, Review of the stability of biochar in soils: Predictability of O:C molar ratios, Carbon Manag. 1 (2010) 289–303. https://doi.org/10.4155/cmt.10.32.

[118] A. Budai, A.R. Zimmerman, A.L. Cowie, J.B.W. Webber, B.P. Singh, B. Glaser, C.A. Masiello, D. Andersson, F. Shields, J. Lehmann, M. Camps Arbestain, M. Williams, S. Sohi, S. Joseph, Biochar Carbon Stability Test Method : An assessment of methods to determine biochar carbon stability, Int. Biochar Initiat. (2013) 1–10. www.biochar-international.org/sites/default/files/IBI_Report_Biochar_Stability_Test_Method_Final.pdf.

[119] M.O. Fagbohungbe, B.M.J. Herbert, L. Hurst, H. Li, S.Q. Usmani, K.T. Semple, Impact of biochar on the anaerobic digestion of citrus peel waste, Bioresour. Technol. 216 (2016) 142–149. https://doi.org/10.1016/j.biortech.2016.04.106.

[120] M.A. Sanchez-Monedero, M.L. Cayuela, A. Roig, K. Jindo, C. Mondini, N. Bolan, Role of biochar as an additive in organic waste composting, Bioresour. Technol. 247 (2018) 1155–1164. https://doi.org/10.1016/j.biortech.2017.09.193.

[121] A. Choudhury, S. Lansing, Biochar addition with Fe impregnation to reduce H2S production from anaerobic digestion, Bioresour. Technol. 306 (2020) 123121. https://doi.org/10.1016/j.biortech.2020.123121.

[122] J.T. Yu, A.M. Dehkhoda, N. Ellis, Development of biochar-based catalyst for transesterification of canola oil, Energy and Fuels. 25 (2011) 337–344. https://doi.org/10.1021/ef100977d.

[123] D. Kołodyńska, R. Wnetrzak, J.J. Leahy, M.H.B. Hayes, W. Kwapiński, Z. Hubicki, Kinetic and adsorptive characterization of biochar in metal ions removal, Chem. Eng. J. 197 (2012) 295–305. https://doi.org/10.1016/j.cej.2012.05.025.

[124] M. Li, Y. Zheng, Y. Chen, X. Zhu, Biodiesel production from waste cooking oil using a heterogeneous catalyst from pyrolyzed rice husk, Bioresour. Technol. 154 (2014) 345–348. https://doi.org/10.1016/j.biortech.2013.12.070.

[125] J.R. Kastner, J. Miller, D.P. Geller, J. Locklin, L.H. Keith, T. Johnson, Catalytic esterification of fatty acids using solid acid catalysts generated from biochar and activated carbon, Catal. Today. 190 (2012) 122–132. https://doi.org/10.1016/j.cattod.2012.02.006.

[126] J.R. Kim, E. Kan, Heterogeneous photocatalytic degradation of sulfamethoxazole in water using a biochar-supported TiO2 photocatalyst, J. Environ. Manage. 180 (2016) 94–101. https://doi.org/10.1016/j.jenvman.2016.05.016.

[127] H. Suopajärvi, E. Pongrácz, T. Fabritius, The potential of using biomass-based reducing agents in the blast furnace: A review of thermochemical conversion technologies and assessments related to sustainability, Renew. Sustain. Energy Rev. 25 (2013) 511–528. https://doi.org/10.1016/j.rser.2013.05.005.

[128] A. Adrados, I. De Marco, A. López-Urionabarrenechea, J. Solar, B.M. Caballero, N. Gastelu, Biomass pyrolysis solids as reducing agents: Comparison with commercial reducing agents, Materials (Basel). 9 (2016) 1–18. https://doi.org/10.3390/ma9010003.

[129] J.H. Park, J.J. Wang, S.H. Kim, S.W. Kang, C.Y. Jeong, J.R. Jeon, K.H. Park, J.S. Cho, R.D. Delaune, D.C. Seo, Cadmium adsorption characteristics of biochars derived using various pine tree residues and pyrolysis temperatures, J. Colloid Interface Sci. 553 (2019) 298–307. https://doi.org/10.1016/j.jcis.2019.06.032.

[130] X.J. Tong, J.Y. Li, J.H. Yuan, R.K. Xu, Adsorption of Cu(II) by biochars generated from three crop straws, Chem. Eng. J. 172 (2011) 828–834. https://doi.org/10.1016/j.cej.2011.06.069.

[131] F.M. Pellera, A. Giannis, D. Kalderis, K. Anastasiadou, R. Stegmann, J.Y. Wang, E. Gidarakos, Adsorption of Cu(II) ions from aqueous solutions on biochars prepared from agricultural by-products, J. Environ. Manage. 96 (2012) 35–42. https://doi.org/10.1016/j.jenvman.2011.10.010.

[132] X. Chen, G. Chen, L. Chen, Y. Chen, J. Lehmann, M.B. McBride, A.G. Hay, Adsorption of copper and zinc by biochars produced from pyrolysis of hardwood and corn straw in aqueous solution, Bioresour. Technol. 102 (2011) 8877–8884. https://doi.org/10.1016/j.biortech.2011.06.078.

[133] J. Sun, F. Lian, Z. Liu, L. Zhu, Z. Song, Biochars derived from various crop straws: Characterization and Cd(II) removal potential, Ecotoxicol. Environ. Saf. 106 (2014) 226–231. https://doi.org/10.1016/j.ecoenv.2014.04.042.

[134] L. Riva, H. Kofoed, Ø. Skreiberg, L. Wang, P. Bartocci, M. Barbanera, G. Bidini, F. Fantozzi, Analysis of optimal temperature , pressure and binder quantity for the production of biocarbon pellet to be used as a substitute for coke, Appl. Energy. 256 (2019) 113933. https://doi.org/10.1016/j.apenergy.2019.113933.

[135] G.R. Surup, A. Trubetskaya, Charcoal as an Alternative Reductant in Ferroalloy Production : A Review, Processes. 8 (2020) 1–41. https://doi.org/10.3390/pr8111432.

[136] L. Riva, L. Wang, G. Ravenni, P. Bartocci, T. Videm, Ø. Skreiberg, F. Fantozzi, H. Kofoed, Considerations on factors affecting biochar densi fi cation behavior based on a multiparameter model, Energy. 221 (2021) 119893. https://doi.org/10.1016/j.energy.2021.119893.

[137] T. Huggins, H. Wang, J. Kearns, P. Jenkins, Z.J. Ren, Biochar as a sustainable electrode material for electricity production in microbial fuel cells, Bioresour. Technol. 157 (2014) 114–119. https://doi.org/10.1016/j.biortech.2014.01.058.

[138] C. Jiang, J. Ma, G. Corre, S.L. Jain, J.T.S. Irvine, Challenges in developing direct carbon fuel cells, Chem. Soc. Rev. 46 (2017) 2889–2912. https://doi.org/10.1039/c6cs00784h.

[139] D. Cao, Y. Sun, G. Wang, Direct carbon fuel cell: Fundamentals and recent developments, J. Power Sources. 167 (2007) 250–257. https://doi.org/10.1016/j.jpowsour.2007.02.034.

[140] Y. Lin, Y. Pan, J. Zhang, CoP nanorods decorated biomass derived N, P co-doped carbon flakes as an efficient hybrid catalyst for electrochemical hydrogen evolution, Electrochim. Acta. 232 (2017) 561–569. https://doi.org/10.1016/j.electacta.2017.03.042.

[141] L. Chen, R. Nakamoto, S. Kudo, S. Asano, J. Hayashi, Biochar-Assisted Water Electrolysis, Energy & Fuels. 33 (2019) 11246–11252. https://doi.org/10.1021/acs.energyfuels.9b02925.

[142] Poonam, K. Sharma, A. Arora, S.K. Tripathi, Review of supercapacitors: Materials and devices, J. Energy Storage. 21 (2019) 801–825. https://doi.org/10.1016/j.est.2019.01.010.

[143] Z. Yang, J. Tian, Z. Yin, C. Cui, W. Qian, F. Wei, Carbon nanotube- and graphene-based nanomaterials and applications in high-voltage supercapacitor: A review, Carbon N. Y. 141 (2019) 467–480. https://doi.org/10.1016/j.carbon.2018.10.010.

[144] C. Dupont, Overview of biochar for electrochemistry applications, in: F. Berruti (Ed.), Biochar Prod. Charact. Appl., UK edition, ECI Symposium, 2017. http://dc.engconfintl.org/cgi/viewcontent.cgi?article=1061&context=biochar.

[145] A.G. Pandolfo, A.F. Hollenkamp, Carbon properties and their role in supercapacitors ☆, J. Power Sources. 157 (2006) 11–27. https://doi.org/10.1016/j.jpowsour.2006.02.065.

[146] S. Vivekanandhan, Biochar Supercapacitors : Recent Developments in the Materials and Methods, in: A. Ahmed (Ed.), Green Sustain. Adv. Mater., Scrivener Publishing LLC, 2018: pp. 223–250. https://doi.org/10.1002/9781119528463.ch10.

[147] F. Cheng, J. Liang, Z. Tao, J. Chen, Functional materials for rechargeable batteries, Adv. Mater. 23 (2011) 1695–1715. https://doi.org/10.1002/adma.201003587.

[148] M. Hassan, Y. Liu, R. Naidu, S.J. Parikh, J. Du, F. Qi, I.R. Willett, Influences of feedstock sources and pyrolysis temperature on the properties of biochar and functionality as adsorbents : A meta-analysis, Sci. Total Environ. 744 (2020) 140714. https://doi.org/10.1016/j.scitotenv.2020.140714.

[149] S.X. Zhao, N. Ta, X.D. Wang, Effect of temperature on the structural and physicochemical properties of biochar with apple tree branches as feedstock material, Energies. 10 (2017) 1–15. https://doi.org/10.3390/en10091293.

[150] J.W. Gaskin, A. Speir, L.M. Morris, L. Ogden, K. Harris, D. Lee, K.C. Das, Potential for Pyrolysis Char to Affect Soil Moisture and Nutrient Status of a Loamy Sand Soil, in: Proc. 2007 Georg. Water Resour. Conf., Georgia, 2007.

[151] Z. Liu, W. Niu, H. Chu, T. Zhou, Z. Niu, Effect of the Carbonization Temperature on the Properties of Biochar Produced from the Pyrolysis of Crop Residues, BioResources. 13 (2018) 3429–3446. https://doi.org/10.15376/biores.13.2.3429-3446.

[152] D.A. Laird, R.C. Brown, J.E. Amonette, J. Lehmann, Review of the pyrolysis platform for coproducing bio-oil ad biochar, Biofuels, Bioprod. Biorefining. 3 (2009) 547–562. https://doi.org/10.1002/bbb.

[153] J. Lehmann, J.P. Silva Jr, C. Steiner, T. Nehls, W. Zech, B. Glaser, Nutrient availability and leaching an in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendements, Plant Soil. 249 (2003) 343–357. https://doi.org/10.1023/A:1022833116184.

[154] J. Mumme, F. Srocke, K. Heeg, M. Werner, Use of biochars in anaerobic digestion, Bioresour. Technol. 164 (2014) 189–197. https://doi.org/10.1016/j.biortech.2014.05.008.

[155] L. Leng, Q. Xiong, L. Yang, H. Li, Y. Zhou, W. Zhang, S. Jiang, H. Li, H. Huang, An overview on engineering the surface area and porosity of biochar, Sci. Total Environ. 763 (2021) 144204. https://doi.org/10.1016/j.scitotenv.2020.144204.

[156] L. Li, S. Liu, J. Liu, Surface modification of coconut shell based activated carbon for the improvement of hydrophobic VOC removal, J. Hazard. Mater. 192 (2011) 683–690. https://doi.org/10.1016/j.jhazmat.2011.05.069.

[157] B. Li, L. Yang, C. quan Wang, Q. pei Zhang, Q. cheng Liu, Y. ding Li, R. Xiao, Adsorption of Cd(II) from aqueous solutions by rape straw biochar derived from different modification processes, Chemosphere. 175 (2017) 332–340. https://doi.org/10.1016/j.chemosphere.2017.02.061.

[158] A.J.M. Stams, C.M. Plugge, Electron transfer in syntrophic communities of anaerobic bacteria and archaea, Nat. Rev. Microbiol. 7 (2009) 568–577. https://doi.org/10.1038/nrmicro2166.

[159] C.W. Wambugu, E.R. Rene, J. van de Vossenberg, C. Dupont, E.D. van Hullebusch, Role of biochar in anaerobic digestion based biorefinery for food waste, Front. Energy Res. 7 (2019) 1–13. https://doi.org/10.3389/fenrg.2019.00014.

[160] Y. Fan, B. Wang, S. Yuan, X. Wu, J. Chen, L. Wang, Adsorptive removal of chloramphenicol from wastewater by NaOH modified bamboo charcoal, Bioresour. Technol. 101 (2010) 7661–7664. https://doi.org/10.1016/j.biortech.2010.04.046.

[161] H.S. Kambo, A. Dutta, A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications, Renew. Sustain. Energy Rev. 45 (2015) 359–378. https://doi.org/10.1016/j.rser.2015.01.050.

[162] B. Shen, J. Chen, S. Yue, G. Li, A comparative study of modified cotton biochar and activated carbon based catalysts in low temperature SCR, Fuel. 156 (2015) 47–53. https://doi.org/10.1016/j.fuel.2015.04.027.

[163] M.R. Yazdani, N. Duimovich, A. Tiraferri, P. Laurell, M. Borghei, J.B. Zimmerman, R. Vahala, Tailored mesoporous biochar sorbents from pinecone biomass for the adsorption of natural organic matter from lake water, J. Mol. Liq. 291 (2019) 111248. https://doi.org/10.1016/j.molliq.2019.111248.

[164] G. Wang, T. Pinto, M. Costa, Investigation on ash deposit formation during the co-firing of coal with agricultural residues in a large-scale laboratory furnace, Fuel. 117 (2014) 269–277. https://doi.org/10.1016/j.fuel.2013.09.084.

[165] N.B. Klinghoffer, M.J. Castaldi, A. Nzihou, Influence of char composition and inorganics on catalytic activity of char from biomass gasification, Fuel. 157 (2015) 37–47. https://doi.org/10.1016/j.fuel.2015.04.036.

[166] J. Alvarez, G. Lopez, M. Amutio, J. Bilbao, M. Olazar, Upgrading the rice husk char obtained by flash pyrolysis for the production of amorphous silica and high quality activated carbon, Bioresour. Technol. 170 (2014) 132–137. https://doi.org/10.1016/j.biortech.2014.07.073.

[167] Metcalf, Eddy, eds., Wastewater Engineering Treatment and Reuse, McGraw-Hil, Metcalf & Eddy, New York, 2003.

[168] X. Dong, L.Q. Ma, Y. Li, Characteristics and mechanisms of hexavalent chromium removal by biochar from sugar beet tailing, J. Hazard. Mater. 190 (2011) 909–915. https://doi.org/10.1016/j.jhazmat.2011.04.008.

[169] W. Zhang, S. Mao, H. Chen, L. Huang, R. Qiu, Pb(II) and Cr(VI) sorption by biochars pyrolyzed from the municipal wastewater sludge under different heating conditions, Bioresour. Technol. 147 (2013) 545–552. https://doi.org/10.1016/j.biortech.2013.08.082.

[170] K.K. Shimabuku, J.P. Kearns, J.E. Martinez, R.B. Mahoney, L. Moreno-vasquez, R.S. Summers, Biochar sorbents for sulfamethoxazole removal from surface water , stormwater , and wastewater effluent, Water Res. 96 (2016) 236–245. https://doi.org/10.1016/j.watres.2016.03.049.

[171] M. Inyang, B. Gao, A. Zimmerman, M. Zhang, H. Chen, Synthesis, characterization, and dye sorption ability of carbon nanotube-biochar nanocomposites, Chem. Eng. J. 236 (2014) 39–46. https://doi.org/10.1016/j.cej.2013.09.074.

[172] X. Cao, L. Ma, B. Gao, W. Harris, Dairy-manure derived biochar effectively sorbs lead and atrazine, Environ. Sci. Technol. 43 (2009) 3285–3291. https://doi.org/10.1021/es803092k.

[173] Á. Guinda, Use of solid residue from the olive industry, Grasas y Aceites. 57 (2006) 107–115. https://doi.org/10.3989/gya.2006.v57.i1.26.

[174] R. Azargohar, A.K. Dalai, Biochar as a precursor of activated carbon, Appl. Biochem. Biotechnol. 131 (2006) 762–773. https://doi.org/10.1385/ABAB:131:1:762.

[175] J. Koopmans, A Koppejan, Agricultural and forestry residues generation, utilization and availability, in: Reg. Consult. Mod. Appl. Biomass Energy, Kuala Lumpur, Malaysia, n.d.

[176] M. Ghaedi, A.M. Ghaedi, F. Abdi, M. Roosta, R. Sahraei, A. Daneshfar, Principal component analysis-artificial neural network and genetic algorithm optimization for removal of reactive orange 12 by copper sulfide nanoparticles-activated carbon, J. Ind. Eng. Chem. 20 (2014) 787–795. https://doi.org/10.1016/j.jiec.2013.06.008.

[177] Y. Yao, B. Gao, H. Chen, L. Jiang, M. Inyang, A.R. Zimmerman, X. Cao, L. Yang, Y. Xue, H. Li, Adsorption of sulfamethoxazole on biochar and its impact on reclaimed water irrigation, J. Hazard. Mater. 209–210 (2012) 408–413. https://doi.org/10.1016/j.jhazmat.2012.01.046.

[178] D.M. Glazunova, P.A. Kuryntseva, S.Y. Selivanovskaya, P.Y. Galitskaya, Assessing the potential of using biochar as a soil conditioner, IOP Conf. Ser. Earth Environ. Sci. 107 (2018). https://doi.org/10.1088/1755-1315/107/1/012059.

[179] S. Baronti, F.P. Vaccari, F. Miglietta, C. Calzolari, E. Lugato, S. Orlandini, R. Pini, C. Zulian, L. Genesio, Impact of biochar application on plant water relations in Vitis vinifera (L.), Eur. J. Agron. 53 (2014) 38–44. https://doi.org/10.1016/j.eja.2013.11.003.

[180] A. Méndez, M. Terradillos, G. Gascó, Physicochemical and agronomic properties of biochar from sewage sludge pyrolysed at different temperatures, J. Anal. Appl. Pyrolysis. 102 (2013) 124–130. https://doi.org/10.1016/j.jaap.2013.03.006.

[181] W.K. Kim, T. Shim, Y.S. Kim, S. Hyun, C. Ryu, Y.K. Park, J. Jung, Characterization of cadmium removal from aqueous solution by biochar produced from a giant Miscanthus at different pyrolytic temperatures, Bioresour. Technol. 138 (2013) 266–270. https://doi.org/10.1016/j.biortech.2013.03.186.

[182] G. Wang, Q. Li, X. Gao, X.C. Wang, Synergetic promotion of syntrophic methane production from anaerobic digestion of complex organic wastes by biochar: Performance and associated mechanisms, Bioresour. Technol. 250 (2018) 812–820. https://doi.org/10.1016/j.biortech.2017.12.004.

[183] D. Meyer-Kohlstock, T. Haupt, E. Heldt, N. Heldt, E. Kraft, Biochar as additive in

biogas-production from bio-waste, Energies. 9 (2016). https://doi.org/10.3390/en9040247.

[184] M. Dudek, K. Świechowski, P. Manczarski, J.A. Koziel, A. Białowiec, The effect of biochar addition on the biogas production kinetics from the anaerobic digestion of brewers' spent grain, Energies. 12 (2019) 1–22. https://doi.org/10.3390/en12081518.

[185] H. Bamdad, K. Hawboldt, S. MacQuarrie, S. Papari, Application of biochar for acid gas removal: experimental and statistical analysis using CO2, Environ. Sci. Pollut. Res. 26 (2019) 10902–10915. https://doi.org/10.1007/s11356-019-04509-3.

[186] J. Guo, Y. Luo, A.C. Lua, R. an Chi, Y. lin Chen, X. ting Bao, S. xin Xiang, Adsorption of hydrogen sulphide (H2S) by activated carbons derived from oil-palm shell, Carbon N. Y. 45 (2007) 330–336. https://doi.org/10.1016/j.carbon.2006.09.016.

[187] A.M. Dehkhoda, A.H. West, N. Ellis, Biochar based solid acid catalyst for biodiesel production, Appl. Catal. A Gen. 382 (2010) 197–204. https://doi.org/10.1016/j.apcata.2010.04.051.

[188] J. Koppejan, S. Sokhansanj, S. Melin, S. Madrali, Status overview of torrefaction technologies, 2012.

[189] D.C. Leonard, Coke quality requirements of European blast furnace engineers, in: Proc. 3rd Eur. Cokemak. Cong, CRM-VDEh, Gent, Belgium, 1996: pp. 1–10.

[190] A. Babich, D. Senk, M. Fernandez, Charcoal behaviour by its injection into the modern blast furnace, ISIJ Int. 60 (2010) 81–88.

[191] D. Andahazy, S. Slaby, G. Löffler, F. Winter, C. Feilmayr, T. Bürgler, Governing processes of gas and oil injection into the blast furnace, ISIJ Int. 46 (2006) 496–502. https://doi.org/10.2355/isijinternational.46.496.

[192] N. Farrokh, P. Sulasalmi, T. Fabritius, Added value for forest industry for metals producing and processing integrates, 2019.

[193] S. Nomura, K. Kato, The effect of plastic size on coke quality and coking pressure in the co-carbonization of coal/plastic in coke oven, Fuel. 85 (2006) 47–56. https://doi.org/10.1016/j.fuel.2005.05.019.

[194] K.W. Ng, L. Giroux, T. MacPhee, T. Todoschuk, Incorporation of charcoal in coking coal blend - A study of the effects on carbonization conditions and coke quality, AISTech - Iron Steel Technol. Conf. Proc. (2012) 225–236.

[195] S. Li, S. Ho, T. Hua, Q. Zhou, F. Li, J. Tang, Sustainable biochar as an electrocatalysts for the oxygen reduction reaction in microbial fuel cells, Green Energy Environ. (2020). https://doi.org/10.1016/j.gee.2020.11.010.

[196] Q. Liu, Y. Zhou, S. Chen, Z. Wang, H. Hou, F. Zhao, Cellulose-derived nitrogen and phosphorus dual-doped carbon as high performance oxygen reduction catalyst in microbial fuel cell, J. Power Sources. 273 (2015) 1189–1193. https://doi.org/10.1016/j.jpowsour.2014.09.102.

[197] D. Angin, E. Altintig, T.E. Köse, Influence of process parameters on the surface and chemical properties of activated carbon obtained from biochar by chemical activation, Bioresour. Technol. 148 (2013) 542–549. https://doi.org/10.1016/j.biortech.2013.08.164.

[198] B.H. Cheng, R.J. Zeng, H. Jiang, Recent developments of post-modification of biochar for electrochemical energy storage, Bioresour. Technol. 246 (2017) 224–233. https://doi.org/10.1016/j.biortech.2017.07.060.

[199] Y. Deng, Y. Xie, K. Zou, X. Ji, Review on recent advances in nitrogen-doped carbons: Preparations and applications in supercapacitors, J. Mater. Chemestry A. 4 (2016) 1144–1173. https://doi.org/https://doi.org/10.1039/C5TA08620E.

[200] S. Liu, Y. Cai, X. Zhao, Y. Liang, M. Zheng, H. Hu, H. Dong, S. Jiang, Y. Liu, Y. Xiao, Sulfur-doped nanoporous carbon spheres with ultrahigh specific surface area and high electrochemical activity for supercapacitor, J. Power Sources. 360 (2017) 373–382. https://doi.org/10.1016/j.jpowsour.2017.06.029.

[201] L. Wang, X. Li, J. Ma, Q. Wu, X. Duan, Non-activated, N, S-co-doped Biochar Derived from Banana with Superior Capacitive Properties, Sustain. Energy. 2 (2014) 39–43. https://doi.org/10.12691/rse-2-2-1.

[202] A. Białowiec, J. Pulka, P. Stępień, P. Manczarski, J. Gołaszewski, The RDF/SRF torrefaction: An effect of temperature on characterization of the product – Carbonized Refuse Derived Fuel, Waste Manag. 70 (2017) 91–100. https://doi.org/10.1016/j.wasman.2017.09.020.

[203] T.G. Bridgeman, J.M. Jones, I. Shield, P.T. Williams, Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties, Fuel. 87 (2008) 844–856. https://doi.org/10.1016/j.fuel.2007.05.041.

[204] M. Ducousso, E. Weiss-Hortala, A. Nzihou, M.J. Castaldi, Reactivity enhancement of gasification biochars for catalytic applications, Fuel. 159 (2015) 491–499. https://doi.org/10.1016/j.fuel.2015.06.100.

[205] M. Laghari, R. Naidu, B. Xiao, Z. Hu, M.S. Mirjat, M. Hu, M.N. Kandhro, Z. Chen, D. Guo, Q. Jogi, Z.N. Abudi, S. Fazal, Recent developments in biochar as an effective tool for agricultural soil management: a review, J. Sci. Food Agric. 96 (2016) 4840–4849. https://doi.org/10.1002/jsfa.7753.

[206] S. Li, V. Barreto, R. Li, G. Chen, Y.P. Hsieh, Nitrogen retention of biochar derived from different feedstocks at variable pyrolysis temperatures, J. Anal. Appl. Pyrolysis. 133 (2018) 136–146. https://doi.org/10.1016/j.jaap.2018.04.010.

[207] S. Rajkovich, A. Enders, K. Hanley, C. Hyland, A.R. Zimmerman, J. Lehmann, Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil, Biol. Fertil. Soils. 48 (2012) 271–284. https://doi.org/10.1007/s00374-011-0624-7.

[208] K. Swiechowski, S. Stegenta-Dabrowska, M. Liszewski, P. Babelewski, J.A. Koziel, A. Białowiec, Oxytree pruned biomass torrefaction: Process kinetics, Materials (Basel). 12 (2019) 1–29. https://doi.org/10.3390/ma12203334.

[209] R. Volpe, A. Messineo, M. Millan, M. Volpe, R. Kandiyoti, Assessment of olive wastes as energy source: Pyrolysis, torrefaction and the key role of H loss in thermal breakdown, Energy. 82 (2015) 119–127. https://doi.org/10.1016/j.energy.2015.01.011.

[210] B. Acharya, Torrefaction and Pelletization of Different Forms of Biomass of Ontario by Bimal Acharya A Thesis Presented to The University of Guelph In partial fulfillment of requirements for the degree of Master of Applied Science in Engineering, The University of Guelph, 2013.

[211] A. Enders, K. Hanley, T. Whitman, S. Joseph, J. Lehmann, Characterization of biochars to evaluate recalcitrance and agronomic performance, Bioresour. Technol. 114 (2012) 644–653. https://doi.org/10.1016/j.biortech.2012.03.022.

[212] D. Chen, Z. Zheng, K. Fu, Z. Zeng, J. Wang, M. Lu, Torrefaction of biomass stalk and its effect on the yield and quality of pyrolysis products, Fuel. 159 (2015) 27–32. https://doi.org/10.1016/j.fuel.2015.06.078.

[213] Y. Uemura, R. Matsumoto, S. Saadon, Y. Matsumura, A study on torrefaction of Laminaria japonica, Fuel Process. Technol. 138 (2015) 133–138. https://doi.org/10.1016/j.fuproc.2015.05.016.

[214] R. Feola Conz, T.F. Abbruzzini, C.A. de Andrade, D.M.B. P. Milori, C. E. P. Cerri, Effect of Pyrolysis Temperature and Feedstock Type on Agricultural Properties and Stability of Biochars, Agric. Sci. 08 (2017) 914–933. https://doi.org/10.4236/as.2017.89067.

[215] F. Ronsse, S. van Hecke, D. Dickinson, W. Prins, Production and characterization of slow pyrolysis biochar: Influence of feedstock type and pyrolysis conditions, GCB Bioenergy. 5 (2013) 104–115. https://doi.org/10.1111/gcbb.12018.

[216] N. Touray, W.T. Tsai, H.R. Chen, S.C. Liu, Thermochemical and pore properties of goat-manure-derived biochars prepared from different pyrolysis temperatures, J. Anal. Appl. Pyrolysis. 109 (2014) 116–122. https://doi.org/10.1016/j.jaap.2014.07.004.

[217] P. Devi, A.K. Saroha, Effect of temperature on biochar properties during paper mill sludge pyrolysis, Int. J. ChemTech Res. 5 (2013) 682–687.

[218] S.D. Ferreira, C. Manera, W.P. Silvestre, G.F. Pauletti, C.R. Altafini, M. Godinho, Use of Biochar Produced from Elephant Grass by Pyrolysis in a Screw Reactor as a Soil Amendment, Waste and Biomass Valorization. 10 (2019) 3089–3100. https://doi.org/10.1007/s12649-018-0347-1.

[219] M.H. Duku, S. Gu, E. Ben Hagan, Biochar production potential in Ghana - A review, Renew. Sustain. Energy Rev. 15 (2011) 3539–3551. https://doi.org/10.1016/j.rser.2011.05.010.

[220] P. Kim, A. Johnson, C.W. Edmunds, M. Radosevich, F. Vogt, T.G. Rials, N. Labbé, Surface functionality and carbon structures in lignocellulosic-derived biochars produced by fast pyrolysis, Energy and Fuels. 25 (2011) 4693–4703. https://doi.org/10.1021/ef200915s.

[221] H. Wu, X. Che, Z. Ding, X. Hu, A.E. Creamer, H. Chen, B. Gao, Release of soluble elements from biochars derived from various biomass feedstocks, Environ. Sci. Pollut. Res. 23 (2016) 1905–1915. https://doi.org/10.1007/s11356-015-5451-1.

[222] J.L. Deenik, M.J. Cooney, The potential benefits and limitations of corn cob and sewage sludge biochars in an infertile Oxisol, Sustain. 8 (2016). https://doi.org/10.3390/su8020131.

[223] M.K. Hossain, V. Strezov Vladimir, K.Y. Chan, A. Ziolkowski, P.F. Nelson, Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar, J. Environ. Manage. 92 (2011) 223–228. https://doi.org/10.1016/j.jenvman.2010.09.008.

[224] X.D. Song, X.Y. Xue, D.Z. Chen, P.J. He, X.H. Dai, Application of biochar from sewage sludge to plant cultivation: Influence of pyrolysis temperature and biochar-to-soil ratio on yield and heavy metal accumulation, Chemosphere. 109 (2014) 213–220. https://doi.org/10.1016/j.chemosphere.2014.01.070.

[225] D. Angin, Effect of pyrolysis temperature and heating rate on biochar obtained from pyrolysis of safflower seed press cake, Bioresour. Technol. 128 (2013) 593–597. https://doi.org/10.1016/j.biortech.2012.10.150.

[226] V. Benedetti, F. Patuzzi, M. Baratieri, Characterization of char from biomass gasification and its similarities with activated carbon in adsorption applications, Appl. Energy. 227 (2018) 92–99. https://doi.org/10.1016/j.apenergy.2017.08.076.

[227] R. Chintala, T.E. Schumacher, S. Kumar, D.D. Malo, J.A. Rice, B. Bleakley, G. Chilom, D.E. Clay, J.L. Julson, S.K. Papiernik, Z.R. Gu, Molecular characterization of biochars and their influence on microbiological properties of soil, J. Hazard. Mater. 279 (2014) 244–256. https://doi.org/10.1016/j.jhazmat.2014.06.074.

[228] J.W. Lee, M. Kidder, B.R. Evans, S. Paik, A.C. Buchanan, C.T. Garten, R.C. Brown, Characterization of biochars produced from cornstovers for soil amendment, Environ. Sci. Technol. 44 (2010) 7970–7974. https://doi.org/10.1021/es101337x.

[229] L.M. Romero Millán, F.E. Sierra Vargas, A. Nzihou, Steam gasification behavior of tropical agrowaste: A new modeling approach based on the inorganic composition, Fuel. 235 (2019) 45–53. https://doi.org/10.1016/j.fuel.2018.07.053.

[230] A.N. Rollinson, Gasification reactor engineering approach to understanding the formation of biochar properties, Proc. R. Soc. A Math. Phys. Eng. Sci. 472 (2016) 20150841. https://doi.org/10.1098/rspa.2015.0841.

[231] L. Fryda, R. Visser, Biochar for Soil Improvement: Evaluation of Biochar from Gasification and Slow Pyrolysis, Agriculture. 5 (2015) 1076–1115. https://doi.org/10.3390/agriculture5041076.

[232] C. Gai, M. Chen, T. Liu, N. Peng, Z. Liu, Gasification characteristics of hydrochar and pyrochar derived from sewage sludge, Energy. 113 (2016) 957–965. https://doi.org/10.1016/j.energy.2016.07.129.

[233] L.M. Romero Millán, F.E. Sierra Vargas, A. Nzihou, Catalytic Effect of Inorganic Elements on Steam Gasification Biochar Properties from Agrowastes, Energy and Fuels. 33 (2019) 8666–8675. https://doi.org/10.1021/acs.energyfuels.9b01460.

[234] Q. Yin, H. Ren, R. Wang, Z. Zhao, Evaluation of nitrate and phosphate adsorption on Al-modified biochar: Influence of Al content, Sci. Total Environ. 631–632 (2018) 895–903. https://doi.org/10.1016/j.scitotenv.2018.03.091.

[235] M.L. Nieva Lobos, J.M. Sieben, V. Comignani, M. Duarte, M.A. Volpe, E.L. Moyano, Biochar from pyrolysis of cellulose: An alternative catalyst support for the electro-oxidation of methanol, Int. J. Hydrogen Energy. 41 (2016) 10695–10706. https://doi.org/10.1016/j.ijhydene.2016.04.041.

[236] T. Chen, L. Luo, S. Deng, G. Shi, S. Zhang, Y. Zhang, O. Deng, L. Wang, J. Zhang, L. Wei, Sorption of tetracycline on H3PO4 modified biochar derived from rice straw and swine manure, Bioresour. Technol. 267 (2018) 431–437. https://doi.org/10.1016/j.biortech.2018.07.074.

[237] J.S. Cha, J.C. Choi, J.H. Ko, Y.K. Park, S.H. Park, K.E. Jeong, S.S. Kim, J.K. Jeon, The low-temperature SCR of NO over rice straw and sewage sludge derived char, Chem. Eng. J. 156 (2010) 321–327. https://doi.org/10.1016/j.cej.2009.10.027.

[238] J. Dai, X. Meng, Y. Zhang, Y. Huang, Effects of modification and magnetization of rice straw derived biochar on adsorption of tetracycline from water, Bioresour. Technol. 311 (2020) 123455. https://doi.org/10.1016/j.biortech.2020.123455.

[239] J.H. Park, Y.S. Ok, S.H. Kim, J.S. Cho, J.S. Heo, R.D. Delaune, D.C. Seo, Evaluation of phosphorus adsorption capacity of sesame straw biochar on aqueous solution: influence of activation methods and pyrolysis temperatures, Environ. Geochem. Health. 37 (2015) 969–983. https://doi.org/10.1007/s10653-015-9709-9.

[240] T. Iwazaki, H. Yang, R. Obinata, W. Sugimoto, Y. Takasu, Oxygen-reduction activity of silk-derived carbons, J. Power Sources. 195 (2010) 5840–5847. https://doi.org/10.1016/j.jpowsour.2009.12.135.

[241] J.F. González, S. Román, J.M. Encinar, G. Martínez, Pyrolysis of various biomass residues and char utilization for the production of activated carbons, J. Anal. Appl. Pyrolysis. 85 (2009) 134–141. https://doi.org/10.1016/j.jaap.2008.11.035.

[242] N. Muradov, B. Fidalgo, A.C. Gujar, N. Garceau, A. T-Raissi, Production and characterization of Lemna minor bio-char and its catalytic application for biogas reforming, Biomass and Bioenergy. 42 (2012) 123–131. https://doi.org/10.1016/j.biombioe.2012.03.003.

[243] J. Zhang, M. Liu, T. Yang, K. Yang, H. Wang, Synthesis and characterization of a novel magnetic biochar from sewage sludge and its effectiveness in the removal of methyl orange from aqueous solution, Water Sci. Technol. 75 (2017) 1539–1547. https://doi.org/10.2166/wst.2017.014.

[244] J.M. Rafi, A. Rajashekar, M. Srinivas, B.V.S.K. Rao, R.B.N. Prasad, N. Lingaiah, Esterification of glycerol over a solid acid biochar catalyst derived from waste biomass, RSC Adv. 5 (2015) 44550–44566. https://doi.org/10.1039/C5RA06613A.

Appendix A

Table A1 Application of biochar in wastewater treatment

Application	Role of biochar	Needed properties	Impacts of properties	Other notes	Reference
Wastewater treatment	Removal of Cu^{2+}	pH of 5-6	The lower the pH value of biochar, the better the adsorption capacity.	pH has more obvious influences for biochar produced at 600°C	[131]
		pH of 5			[130]
		pH of 5			[123]
		pH of 5			[132]
	Removal of Zn^{2+}	pH of 5		-	[123]
	Removal of Cu^{2+} and Zn^{2+}	pH of 5		pH influences higher for biochar produced at 600C	[132]
	Removal of Cr^{6+}	pH of 2		Carboxylate and hydroxyl groups play an important role in Cr adsorption	[168]
		pH of 2.			[169]
	Removal of Cd	pH of 5-8.		-	[129]
	Removal of antibiotics (Ciprofloxacin)	SSA: 176 $m^2 \cdot g^{-1}$ and solution pH of 7.	High specific offers more active adsorption sites, which can be produced at a pyrolysis temperature of app 800°C.	-	[76]
	Removal of antibiotics	SSA of 499 $m^2 \cdot g^{-1}$		-	[170]
	Removal of sulfonamide antibiotics	pH (different values depending on the type of sulfonamide)	Sorption dominated by the electrostatic interactions between the antibiotics and functionalized biochar surface	Sorption capacity of antibiotic mixtures is three times lower than the one using single antibiotic solutions.	[70]
	Removal of pharmaceutical pollutants (salicylic acid and ibuprofen)	pH of 6 and 8 for salicylic acid and ibuprofen respectively	-	-	[77]
	Removal of methyl violet (dye)	Alkaline pH (7.7-8.7), high amount of soluble salts	-	-	[79]
	Removal of methyl blue (dye)	pH=7, low ionic strength	Adsorption was improved with increasing pH (up to pH=7)	-	[171]
	Removal of atrazine	High carbon content	-	-	[172]

A2 Application of biochar in soil amendment

Application	Role of biochar	Needed properties and performance	Impacts of properties	Other notes	Ref
Soil amendment	Carbon sequestration	Biochar yield. 1.7Mt biochar is equivalent to 2.6Mt CO_2 stored long-term.	The higher yield, the lager value of C stored long-term.	-	[173]
		Biochar yield. 2.5Mt biochar is equivalent to		-	[174]

		2.9 Mt CO_2 stored long-term.			
		Biochar yield. 2.9Mt biochar is equivalent to 5.9 Mt CO_2 stored long-term.		-	[175]
		Biochar yield. 4.9Mt biochar is equivalent to 9.9 Mt CO_2 stored long-term.		-	
		Biochar yield. 16.0Mt biochar is equivalent to 25.6 Mt CO_2 stored long-term.		-	
		Biochar yield. 37.3Mt biochar is equivalent to 55.1 Mt CO_2 stored long-term.		-	[176]
		Biochar yield. 79.7Mt biochar is equivalent to 85.9 Mt CO_2 stored long-term.		-	
		Biochar yield. 83.2Mt biochar is equivalent to 105.7 Mt CO_2 stored long-term.		-	
		Biochar yield. 182.1Mt biochar is equivalent to 313.8 Mt CO_2 stored long-term.		-	
	Soil Productivity and Nutrients recycling	SSA of 0.7 $cm^2 \cdot g^{-1}$. Adsorption capacity of NH_4^+ was 190 $mg \cdot kg^{-1}$	The larger specific surface area, the more adsorption capacity.		[177]
		SSA of 81.1 $cm^{-1} \cdot g^{-1}$. Adsorption capacity of NH_4^+ was 595 $mg \cdot kg^{-1}$			
		SSA of 234.7 $cm \cdot kg^{-1}$. Adsorption capacity of NH_4^+ was 785 $mg \cdot kg^{-1}$			
	Soil conditioner	pH 5.80. Electrical conductivity was 1.02 $mS \cdot cm^{-1}$	The higher pH, the better electrical conductivity.		[178]
		pH 7.40. Electrical conductivity was 6.42 $mS \cdot cm^{-1}$			
		Ash 33.85%, TOC content was 12.36%	The higher ash content, the higher TOC content.		
		Ash 54.85 %, TOC content was 24.93%			
		SSA of 410 $m^2 \cdot g^{-1}$. CEC was 101cmol kg^{-1}	The larger specific surface area, the better CEC.		[179]
		SSA of 33 $m^2 \cdot g^{-1}$. CEC was 30 $cmol \cdot kg^{-1}$			[180]
		SSA of 0.56 $m^2 \cdot g^{-1}$, CEC was 12 $cmol \cdot g^{-1}$			[181]

A3 Application of biochar in biogas production

Application	Role of biochar	Needed properties and performance	Impacts of properties	Other notes	Reference
Biogas production	Buffering	pH＞7	Alkaline biochar is better for biogas production.	-	[182]
		Ash content 3.10 %;	The higher ash	Trace elements of	[183]

		Higher heating value 20.00 MJ·kg^{-1}. Biogas production 61 dm3·kg^{-1}.	content, the more biogas is produced.	biochar are the most important for gas production	
		Ash content 6.70 %; Higher heating value 24.90 MJ·kg^{-1}. Biogas production 122 dm3·kg^{-1}.		-	[184]
		pH 6, Ash 4%, Volatile matter 12 %, Fixed carbon 83 %.		-	[159]
		pH 8, Ash 20%. Volatile matter 18 %, Fixed carbon 33 %.		-	[159]

A4 Application of biochar in flue gas cleaning

Application	Role of biochar	Needed properties and performance	Impacts of properties	Other notes	Reference
Flue gas cleaning	Remove NOx	SSA 17.9 $m^2 \cdot g^{-1}$ and pore volume 0.018 $cm^2 \cdot g^{-1}$. Removal 10% of NOx	Higher specific surface area and larger pore volume can increase NOx adsorption capacity.	As temperature increased, NOx removal efficiency was reduced and, however, the NOx removal efficiency increased again, making the efficiency curve V-shaped. Transitional metal oxides can also enhance the NOx removal.	[162]
		SSA 63.9 $m^2 \cdot g^{-1}$ and pore volume 0.039 cm^3/g. Removal 30% of NOx			
		SSA 782.6 $m^2 \cdot g^{-1}$ and pore volume 0.606$cm^2 \cdot g^{-1}$. Removal 46% of NOx.			
		SSA 139. $m^2 \cdot g^{-1}$ and pore volume 0.092 $cm^2 \cdot g^{-1}$. Removal 50% of NOx			[162]
		SSA 363.0 $m^2 \cdot g^{-1}$ and pore volume 0.164 $cm^2 \cdot g^{-1}$. Removal 71 % of NOx			
		SSA 772.3 $m^2 \cdot g^{-1}$ and pore volume 0.422 $cm^2 \cdot g^{-1}$ Removal 86 % of NOx			
	Remove H_2S	SSA 95.6 to 83.9 $m^2 \cdot g^{-1}$. 12% reduction in adsorption capacity	Lager specific surface area and pore volume had better dynamic adsorption performances.	Different activation agents have a significant effect on the performances.	[185]
		SSA 1062 $m^2 \cdot g^{-1}$ and pore volume $cm^2 \cdot g^{-1}$ 0.26. Adsorption capacity 46 $m \cdot g^{-1}$			[186]
		Fe-impregnated can increase the reduction of H2S by more than 50%.	Fe-impregnated can effectively remove H2S	stover biochar (CSB) and maple wood biochar	[121]

A5 Application of biochar in catalysts

Application	Role of biochar	Needed properties and performance	Impacts of properties	Other notes	Reference
Catalysts	Convert feedstock to into	SSA 1.88 $m^2 \cdot g^{-1}$; transesterification yield 7.6 %	Increase in specific surface area and pore volume of biochar	-	[122]

	fuels	SSA 640 $m^2 \cdot g^{-1}$; transesterification yield 18.9%	resulting in increased reaction yield	-	
		SSA 2.74 $m^2 \cdot g^{-1}$, $–SO_3H$ density 0.6 $mmol \cdot g^{-1}$. FFA conversion 88%	Biodiesel production increased as the more $–SO_3H$ groups, and the larger the specific surface area and pore volume.	-	[187]
		SSA 5.84 $m^2 \cdot g^{-1}$, $–SO_3H$ density 0.65 $mmol \cdot g^{-1}$. FFA conversion 89%		-	
		Pore volume 0.13-0.2 $cm^3 \cdot g^{-1}$; Ester yield 70%		-	[125]
		Pore volume 0.46 $cm^3 \cdot g^{-1}$; Ester yield 97%		-	
		SSA 4 $m^2 \cdot g^{-1}$. FAME yield 87.57%.		-	[124]
		SSA 376 $m^2 \cdot g^{-1}$. FAME yield 90%.		-	[34]

A6 Application of biochar in metal industry

Application	Role of biochar	Needed properties	Impacts of properties	Other notes	Reference
Metal industry	As reductant	SSA 363-375m2/g, pore volume 0.15-0.16 cm3/g. reactivity 86.1-87.8%. Volatile matter 10.0-11.8%.	Higher specific surface area and pore volume, much higher reactivity.	-	[128]
		SSA 444-501, pore volume 0.19-0.21reactivity 93.7%, Volatile matter 8.6-12.0%.		-	
		Volatile Matter 20–25%, Fixed carbon 20–25%.		-	[188]
		Volatile Matter 55–65%, Fixed carbon 28–45%.		-	
		Volatile Matter 10–12%, Fixed carbon 85–87 %.		-	
		Volatile matter < 1.0%; Ash 8–12%; Sulphur 0.5– 0.9%; Phosphorous 0.02–0.06%; Alkalies < 0.3%.		The optimum values are determined by the characteristics and operating conditions of the blast furnaces.	[189]
		Ash 3.2%		-	[10]
		Ash 0.5%		-	
		Ash 1.9%		-	
		HHV 18.0%, FC18.2%, VM 77.0%, Ash 4.8%.		-	[190]
		HHV 32.1%, FC38.7%, VM 61.3%, Ash 15.7%.		-	[189]
		HHV 30.3%, FC1.26%, Ash 11.7%.		-	[191]
	As fuel	VM21.4%, FC68.4%, Ash 10.1%, HHV 30.53 MJ/kg.	Higher carbon content (lower VM) and heating value, the better the performance of	-	[192]
		VM 41.0 %, FC 59.2 %, Ash 0.5%,		-	

		HHV 30.18 MJ/kg at 300℃.	biochar as fuel.		
		VM18.0%, FC 83 %, Ash 0.7%, HHV 33.12 MJ/kg at 500℃.		-	
		VM 5.1 %, FC 94 %, Ash 0.9%, HHV 34.31 MJ/kg at 650 ℃.		-	
		Lower biomass size 3–10 mm.	As the size and density of biomass increased, the contact area and the interaction between the biomass and coal grains decreased	-	[193]
		Size 6.4-9.5mm, total Reactive 71.6%, Cold Strength 26.8. Hot Strength (CSR) 45.8.		-	[194]
		Size <0.07mm, total Reactive 69.5%, Cold Strength 58.9. Hot Strength (CSR) 34.2.		-	

A7 Electrochemical applications

Application	Role of biochar	Needed properties and performance	Impacts of properties	Other notes	Reference
Microbial Fuel cells	Electrodes	Specific surface area and the average pore size	Microporosity is important for increased power density as micropores may contribute to the increased conductivity due to increased specific surface area for electron transfer.	-	[137]
		SSA, porosity and electrical conductivity	Higher specific surface area (higher porosity) of the material is one of the important properties of the cathode in favour. Biochar synthesized at higher temperatures has a higher content of pyrrolic, graphitic and pyridinic nitrogen, which can further facilitate electron transfer when used as a cathode catalyst in MFCs. The catalytic performance of biochar was greatly enhanced by chemical activation.	-	[195]
		Nitrogen-doped biochar and heteroatom-doped biochar	N and P dual-doped carbon from cellulose yielded a higher power density.	-	[196]

Electrolysis	electrocatalyst and photocatalyst	At 550 °C, SSA was 9 m^2/g and current density was 0.65 mA/cm^2. At 650-850 °C, with the surface area increase to 310−450 m^2/g, the current density rose to 1.5−2.5 mA/cm^2. A further increase in TC to 950−1050 °C caused both a current density and surface area decrease.	With the increase of the specific surface area, the current density increases. However, SSA is not necessarily the only property that determines its electrochemical reactivity. the chemical degree of carbonization is another important factor, which is primarily represented by H/C and O/C atomic ratios	increasing electrical conductivity of biochar could contribute to the increase in the current density.	[141]
Supercapacitors and batteries	Electrodes	Specific surface area and the average pore size	The capacitance of a device is largely dependent on the characteristics of the electrode material; particularly, the surface-area and the pore-size distribution. Increases in specific surface-area, generally lead to increased capacitance	-	[145]
		Activation	The activation process on the biochar improves its SSA and pore fraction/distribution to meet the demand for energy storage and conversion processes	-	[197]
		Metal, Metal Oxide and Metal Hydroxide Loading	Biochar modification by loading metals (Ni), metal oxides (MnO_2) and metal hydroxides ($Ni(OH)_2$) is the unique approach to improve the capacitive performance of the biochar.	This modification can be performed either on the surface or throughout the biochar network	[198]
		Nitrogen and Sulfur Doping	The incorporation of various heteroatoms including N, P and S, into carbon architecture improves the electrical conductivity by enhancing the wettability of	-	[199–201]

			electrode in an aqueous electrolyte system.		

Appendix B:

Table B1: Properties of biochar produced from torrefaction

Feedstock		Operation conditions			T (℃)	Physiochemical properties										Reference
		Size (mm)	Residence Time (minutes)	Media		SSA (m^2/g)	V_{micro} (cm^3/g)	pH (H_2O)	H/C	O/C	HHV (MJ/kg)	Proximate analysis			Yield (%)	
												VM (%)	Ash (%)	FC (%)		
Woody biomass (WD)	Sawdust	-	60	-	200	-	-	-	1.3	-	-	77	0.7	-	94	[202]
					300	-	-	-	0.5	-	-	40	1.7	-	30	
	RDF (Refuse Derived Fuel)	-	60	-	200	-	-	-	1.4	-	-	-	14	-	82	
					260	-	-	-	1	-	-	57	24	-	64	
	Willow	-	30	N_2	230	-	-	-	-	-	20.2	82.1	1.8	16.0	95.1	[203]
					250	-	-	-	-	-	20.6	79.8	1.9	18.4	89.6	
					270	-	-	-	-	-	21.8	79.3	2.1	18.6	79.8	
					290	-	-	-	-	-	21.9	77.3	2.3	20.5	72.0	
	Wood chips	40	120	N_2	280	530.5	0.216	-	-	-	-	-	-	-	-	[204]
			240		280	475.1	0.207	-	-	-	-	-	-	-	-	
			480		280	464.1	0.204	-	-	-	-	-	-	-	-	
			120		340	627.1	0.301	-	-	-	-	-	-	-	-	
			120		400	666.8	0.323	-	-	-	-	-	-	-	-	
	Black locust wood	-	-	-	300	-	-	5.7	-	-	-	-	-	-	42	[205]
	Pitch pine	-	-	-	3	-	-	-	-	-	-	-	-	-	60	

	wood chips				00										.7	
	Water oak	-	-	Nitrogen	200	2.77	0.026	4.5	0.108	0.575	-	75.66	2.54	19.13	74.5	[206]
	Wood	-	-	Nitrogen	200	13.62	-	-	-	-	-	-	-	-	84.17	[6]
					260	29.17	-	-	-	-	-	-	-	-	77.01	
					300	33.15	-	-	-	-	-	-	-	-	66.13	
					300	147.02	-	-	-	-	-	-	-	-	43.36	
					300	43.9	-	-	5.9	35.68	-	-	0.3	-	-	
	Pine wood shavings	-	-	-	150	1.8	-	-	12.6	88.62	-	-	1	-	88.9	
					250	5.9	-	-	7.45	62.91	-	-	1.7	-	64.7	
	Coconut coir	-	-	-	250	1.7	-	-	9.27	62.94	-	-	-	-	-	[15]
	Pine needle litters	-	-	-	100	0.7	-	-	12.18	83.1	-	-	0.9	-	91.2	
					300	19.9	-	-	6.24	37.3	-	-	1.9	-	48.6	
	Pine needle	-	-	-	300	4.1	-	-	5.23	9.03	-	-	7.2	-	57.6	
	Hazelnut	-	80-90	CO_2	300	224	-	6.35	-	-	-	48.79	1.98	49.23	-	[207]
	Pine	-	80-90	CO_2	300	157	-	6.74	-	-	-	55.32	1.48	43.20	-	
	Oak	-	80-90	CO_2	300	163	-	4.25		-	-	61.13	0.35	38.52		
	Oxytree pruning	-	20	CO_2	200	-	-	-	-	-	-	-	-	-	97	[208]
			60		300	-	-	-	-	-	-	-	-	-	52	
	Olive trimmings	10	30	N_2	200	-	-	-	0.12	0.70	-	77.09	4.74	16.54	-	[209]
					250	-	-	-	0.11	0.54	-	72.82	4.69	21.73	-	
					300	-	-	-	0.09	0.31	-	64.34	4.71	29.33	-	
					325	-	-	-	0.07	0.18	-	55.96	7.87	32.57	-	

			45		200	-	-	-	0.12	0.70	-	77.65	4.82	16.79	-	
					250	-	-	-	0.11	0.58	-	72.63	3.87	22,23	-	
					300	-	-	-	0.08	0.30	-	61.71	6.82	30.62	-	
	Olive Pulp	1	30		200	-	-	-	0.12	0.72	-	74.7	2.61	21.68	-	
					250	-	-	-	0.10	0.50	-	66.26	2.91	29.19	-	
					300	-	-	-	0,08	0,29	-	49.73	4.52	43.32	-	
					325	-	-	-	0.08	0.24	-	48.91	6.67	43.07	-	
			45		200	-	-	-	0.12	0.72	-	77.22	1.50	19.98	-	
					250	-	-	-	0.10	0.44	-	64.43	3.45	30.77	-	
					300	-	-	-	0.07	0.23	-	41.99	5.31	50.40	-	
	Lodgepole pine grind	2	-	N_2	160	-	-	-	1.31	0.99	20.58	80.35	0.92	18.43	-	[178]
					180	-	-	-	1.28	0.69	20.95	80	1.21	18.79	-	
					230	-	-	-	1.19	0.70	21.34	76.18	1.58	22.34	-	
					270	-	-	-	0.88	0.41	23.21	58.22	1.77	41.01	-	
Animal waste (AW)	Poultry litter	-	15	-	210	-	-	-	-	-	21.06	70.44	12.96	16.46	-	[210]
			45	-	300	-	-	-	-	-	24.56	47.12	30.13	25.02	-	
	Bull manure	-	-	-	300	-	-	8.3	0.61	0.2	-	-	7.6	-	42	[211]
	Poultry manure	-	-	-	300	-	-	9.3	1.47	1.01	-	-	46.5	-	73.8	
	Digested dairy manure	-	-	-	300	-	-	9.3	0.61	0.2	-	-	38.9	-	42	
	Raw dairy manure	-	-	-	300	-	-	9.3	0.61	0.2	-	-	27	-	42	
	Food waste	-	-	-	300	-	-	-	-	-	-	-	22.9	-	42	
	Cattle manure	-	-	-	250	1.4	-	7.9	-	-	-	-	8.6	-	-	[15]

	Dairy manure	-	-	-	200	2.6	-	7	10.93	153.69	-	-	-	-	-	
	Human manure	-	-	-	300	7.3	-	-	15.62	103.5	-	-	26.6	-	51.9	
	Sow manure	-	-	-	300	3.8	-	8.9	8.33	30.47	-	-	43.9	-	60	
	Turkey litter	-	-	-	350	2.6	-	-	7.30	31.24	-	-	34.8	-	58.1	
	Weaner manure	-	-	-	300	3.8	-	-	7.49	26.87	-	-	45.4	-	59.5	
Biosolidssludge (BS)	Municipal waste	-	60	-	200	-	-	-	1.3	-	-	-	14	-	89	
					300	-	-	-	0.4	-	-	-	23	-	63	
	Paper mill sludge	-	-	-	300	-	-	7.8	0.33	1.05	-	-	50.5	-	73	[211]
	Biosolids	-	-	-	200	66.58	0.057	6.17	0.097	0.541	-	33.14	52.33	11.18	75.3	[206]
	Pine pitch	-	-	-	300	2.9	-	-	8.45	47.57	-	-	4.5	-	60.7	[15]
	Sludge	-	-	-	300	-	-	5.3	9.77	32.42	-	-	52.8	-	72.3	
Herbaceous (HB)	Reed canary grass	20	30	N_2	230	-	-	-	-	-	-	-	-	-	92.6	[203]
					250	-	-	-	-	-	20.0	80.3	6.4	13.3	84.0	
					270	-	-	-	-	-	20.8	76.3	7.3	16.1	72.0	
					290	-	-	-	-	-	21.8	70.5	8.3	21.3	64.5	
	Wheat straw				230	-	-	-	-	-	19.4	-	-	-	91	
					250	-	-	-	-	-	19.8	77.0	7.4	15.6	82.6	
					270	-	-	-	-	-	20.7	65.2	8.4	26.5	71.5	
					290	-	-	-	-	-	22.6	51.8	10.2	38.0	55.1	
	Cotton stalk	20-30	30	N_2	220	189.72	-	-	-	-	24.83	34.65	15.08	50.27	-	[212]
					250	203.55	-	-	-	-	26.35	30.52	14.92	54.56	-	
					280	211.63	-	-	-	-	25.06	31.05	15.22	53.73	-	

	Corn	-	80-90	CO_2	300	141	-	7.33	-		-	51.87	10.70	37.43		[207]
	Rice straw	-	-	-	300	-	-	9.19	-	-	-	40.2	22.9	-	50.1	[205]
	Magnolia leaves	-	-	-	300	-	-	-	-	-	-	-	-	-	61.6	
	Switchgrass	-	-	-	200	4.16	0.022	6.97	0.103	0.6002	-	81.02	3.13	12.46	69.9	[206]
	Grass	-	-	-	200	3.3	-	-	15.04	95.55	-	-	-	-	-	[15]
	Miscanthus	-	-	-	300	0.6	-	8.3	8.03	37.52	-	-	2.2	-	53.8	
	Orange peel	-	-	-	150	7.8	-	-	12.25	81.03	-	-	0.5	-	82.4	
	Rice straw	-	-	-	100	-	-	-	6.43	107.24	-	-	18.5	-	-	
Aquatic biomass(AB)	Macroalga Spirulina Platensis	40	30	N_2	200	-	-	-	0.14	0.51	22.0	72.0	5.0	19.0	-	[203]
	Miicroalga Laminaria japonica	0–63 μm	10	-	300	-	-	-	0.82	0.42	79				51	[213]

*- = Not available

Table **B2 Properties of biochar produced from slow pyrolysis**

Feedstock		Operation conditions				T (°C)	Physical properties		Chemical properties								Reference
		Size (mm)	Heating rate (°C/min-^{1})	Detention time (min)	Media		SSA (m^2/g)	V_{micro} (cm^3/g)	pH (H_2O)	H/C	O/C	HHV (MJ/kg)	VM (%)	Ash (%)	FC (%)	Yield (%)	
Woody biomass (WD)	Sawdust	< 1 mm	10	-	N_2	350	-	-	7.6	0.05	0.34	-	54.0	1.2	41.5	42.6	[214]
						450	-	-	7.0	0.06	0.32	-	50.0	0.9	45.6	42.4	
						550	-	-	7.4	0.04	0.21	-	35.3	1.0	60.3	36.4	
						650	-	-	7.5	0.03	0.15	-	29.1	1.2	66.5	33.3	
	Willow chips	-	-	-	-	350	0.17	-	-	-	-	-	-	-	-	-	[205]
	Vine yard pruning	-	-	-	-	475	92	-	-	-	-	-	-	-	-	-	
	Black wattle	-	-	-	-	475	241	-	-	-	-	-	-	-	-	-	
	Softwood pine	-	-	-	-	500	4.9	-	-	-	-	-	-	-	-	-	
	Walnut shell	-	-	-	-	900	227	-	-	-	-	-	-	-	-	-	
	Hardwood	-	-		-	520	164	-	-	-	-	-	-	-	-	-	
						538	7.2	-	-	-	-	-	-	-	-	-	
	Apple wood	-	-	-	-	600	-	-	-	-	-	-	-	-	-	-	
	Spotted gum wood	-	-	-	-	400	-	-	-	-	-	-	-	-	-	51	
	Black locust wood	-	-	-	-	400	-	-	8.1	-	-	-	-	-	-	-	
						500	-	-	8.6	-	-	-	-	-	-	24	
	Pine chips	-	-	-	-	550	-	-		-	-	-	-	-	-	30	
	Sawdust	-	-	-	-	500	-	-	10.5	-	-	-	9.94	17.5	-	-	
						5	-	-		-	-	-	-	-	-	28	

						50											
	Water oak	-	-	-	-	400	17.57	0,023	8.56	4.23	13.95	-	72.13	4.7	22.50	38.7	[206]
						600	32.13	0.026	8.99	3.23	8.59	-	70.75	5.59	23.33	25.8	
						800	52.72	0.028	10.25	3.03	8.69	-	69.55	5.66	24.51	25.6	
	Apple branch	-	10	600	-	400	11.9	-	7	5.84	29.34	-	-	-	-	28.3	[15]
						800	545.4	-	10	0.71	6.84	-	-	-	-	15.5	
	Pepper wood	-	10	600	-	450	0.7	-	9.4	4.76	22.75	-	-	-	-	-	
						600	234.7	-	9.7	2.86	22.99	-	-	-	-	-	
	Eucalyptus	-	5	30	-	400	10.4	-	7.5	6.94	23.52	-	-	-	-	-	
	Hardwood	-	-	-	-	450	0.4	-	5.6	4.31	10.67	-	-	38.6	-	-	
	Palm bark	-	5	30	-	400	2.5	-	7.1	7.84	30.19	-	-	-	-	-	
	Pine wood shavings	-	-	-	-	350	166	-	-	3.98	45.57	-	-	2.3	-	32.6	
						700	637	-	-	1.18	11.07	-	-	4.7	-	15.3	
	Rubber wood sawdust	-	-	-	-	450	-	-	-	3.89	17.01	-	-	14.5	-	41.9	
						850	-	-	-	1.18	0.54	-	-	20	-	28.9	
	Green waste (shredded leaves, twigs, branches)	2	17	10	N_2	300	-	-	7.4	1.41	-	-	74.3	3.6	25.7	98.4	[215]
				60			-	-	8.1	0.94	-	-	48.6	6.8	51.4	48.6	
				10		450	-	-	9.6	0.63	-	27.5	25.3	11.1	74.7	31.3	
				60			17	-	10.0	0.51	-	27.9	18.5	12.0	81.5	27.8	
				10	-	600	-	-	10.4	0.32	-	27.9	11.5	13.2	88.5	24.4	
				60			46	-	11.3	0.27	-	28.0	8.8	13.4	91.2	24.9	
				10		750	-	-	11.4	0.21	-	-	3.5	13.9	96.5	26.4	
				60			-	-	11	0.	-	-	1.	13	98	23	

									.6	16			9	.4	.1	.7	
	Wood	-	17	10	N_2	300	-	-	4.5	1.3	-	-	78.0	0.3	22.0	89.8	
				60			6	-	5.7	0.79	-	-	42.6	0.5	57.4	43.7	
				10		450	4	-	6.6	0.56	-	32.5	21.4	1.0	78.6	29.2	
				60			23	-	6.7	0.49	-	32.9	16.8	1.2	83.2	27.0	
				10	-	600	196	-	6.7	0.35	-	34.4	8.2	1.2	91.8	24.4	
				60			127	-	9.1	0.30	-	34.4	6.4	1.3	93.6	23.3	
				10		750	128	-	10.2	0.19	-	-	2.6	1.1	97.4	23.0	
				60			-	-	10.4	0.15	-	-	2.6	1.1	97.4	22.7	
	Apple tree branches	0.25	10	130	N_2	300	2.39	0.00013	7.48	1	0.29	-	60.77	6.72	32.50	-	[149]
						400	7.00	0.00052	-	-	-	-	29.85	7.85	62.30	-	
						500	37.24	0.00158	11.62	-	-	-	23.19	10.06	66.75	-	
						600	108.59	0.03787	10.60	0.41	0.06	-	14.86	9.40	75.73	-	
Animal waste (AW)	Bull manure	-	-	-	-	400	-	-	9.3	0.61	0.2	-	-	9.0	-	31	[211]
						500	-	-	9.3	0.61	0.2	-	-	10.0	-	26	
						600	-	-	9.3	0.61	0.2	-	-	11	-	21	
	Poultry manure	-	-	-	-	400	-	-	9.3	1.47	1.01	-	-	51.5	-	67.7	
						500	-	-	9.3	1.47	1.01	-	-	52.5	-	66.1	
						600	-	-	9.3	1.47	1.01	-	-	56.1	-	64.9	
	Digested dairy manure	-	-	-	-	400	-	-	9.3	0.61	0.2	-	-	14.3	-	31	
						500	-	-	9.3	0.61	0.2	-	-	14.3	-	26	
						600	-	-	9.3	0.61	0.2	-	-	18.9	-	21	
	Raw	-	-	-	-	4	-	-	9.	0.	0.	-	-	29	-	31	

	dairy manure					00			3	61	2						
						500	-	-	9.3	0.61	0.2	-	-	32	-	26	
						600	-	-	9.3	0.61	0.2	-	-	32	-	21	
	Poultry litter	-	-	-	-	350	-	-	10.2	-	-	-	-	-	-	-	
						450	-	-	10.45	-	-	-	-	-	-	-	
						550	-	-	10.75	-	-	-	-	-	-	-	
						600	-	-	5.79	-	-	-	-	-	-	-	
	Farm manure	-	-	-	-	550	-	-	9.7	-	-	-	-	-	-	-	
	Cow manure	-	-	-	-	500	-	-	10.2	-	-	-	17.2	67.5	-	-	
	Pig manure	-	-	-	-	350	-	-	9.65	-	-	-	27.4	37.2	-	-	
						600	-	-	17	-	-	-	-	-	-	-	
	Swine manure	-	-	-	-	600	3.4	-	0.0013	-	-	-	-	-	-	-	
	Turkey litter	-	-	-	-	700	21.8	-	-	-	-	-	-	-	-	-	
	Broiled litter	-	-	-	-	350	94	-	-	8.77	40.13	-	-	-	-	-	
						700	60	-	-	3.04	16.09	-	-	-	-	-	
	Cattle manure	-	-	-	-	550	58.6	-	10.3	-	-	-	-	18.6	-	-	
						700	-	-	-	2.43	26.21	-	-	72.4	-	-	
	Poultry litter	< 1 mm	10	-	N_2	350	-	-	8.2	-	-	-	60.8	38.2	0.0	59.6	[214]
						450	-	-	9.8	-	-	-	46.9	51.0	1.0	47.1	
						550	-	-	9.8	-	-	-	45.7	50.3	2.8	42.0	
						650	-	-	9.9	-	-	-	42.1	48.8	7.5	40.2	
	Goat-manure-derived biochar	-	10	30	N_2	400	3.27	0.0013	-	-	-	15.85	31	37.3	31	44.5	[216]
						5	1.	0.0	-	-	-	16.	21	41	36	40	

						00	68	013				0				.6	
						600	13.92	0.0078	-	-	-	16.3	16	44	37	37.9	
						700	39.08	0.0199	-	-	-	16.15	14	45	36	35.5	
						800	93.49	0.049	-			16.05	12.5	49	35	33.8	
Biosolids sludge (BS)	Sludge	0.5-1.25	10	-	N_2	300	4.8	-	7.26	-	-	-	-	-	-	-	[217]
						500	47	-	7.28	-	-	-	-	-	-	-	
						600	50	-	7.45	-	-	-	-	-	-	-	
	Organic fraction of dumpsite	-	5	30	-	300	-	0.013	9.70	0.04	0.24	-	31.6	15.6	46.5	-	[78]
						400	-	0.002	8.31	0.09	0.24	-	26.2	5.01	23.3	-	
						500	-	0.039	-	0.03	0.19	-	-	-	-	-	
						700	-	0.05	8.00	0.15	0.34	-	26.4	9.2	63.8	-	
Herbaceous (HB)	Corn cob	-	-	-	-	550	-	-	9.2	-	-	-	9.64	5.61	84.8	-	[179]
	Elephant grass	-	10	-	N_2	0	-	-	7.0	1.79	1.08	15.97	82.39	8.07	9.53	-	[218]
						400	17.27	0.001	9.9	-	-	-	21.77	23.1	49.33	-	
						500	21.41	0.006	9.9	-	-	-	13.93	28.93	51.25	-	
						600	17.92	0.000	10.0	-	-	-	8.81	30.31	54.64	-	
	Cotton seed hull	-	-	-	-	800	58	0.078	-	-	-	-	19.85	72,4	6,96	35	[206]
	Rice	-	-	-	-	300	-	-	-	1.33	0.39	-	62.35	16.57	21.08	-	[148]
						400	-	-	-	0.81	0.22	-	32.21	26.71	41.09	-	
						500	-	-	-	0.76	0.16	-	23.60	30.49	45.92	-	
						600	-	-	-	0.48	0.10	-	16.34	33.36	50.30	-	
						700	-	-	-	0.41	0.09	-	14.01	37.91	48.08	-	
	Peanut	-	-	-	-	7	44	0.2	10	2.	15	-	-	8.	-	21	[15]

	shells					00	8.2		.6	15	.87			9		.9	
	Rice husk	-	-	-	-	350	27.8	-	8	-	-	-	-	-	-	-	
	Sugarcane bagasse	-	-	-	-	400	5.7	-	-	2.39	49.28	-	-	43.5	-	-	
						600	388.3	-	77	3.08	22.85	-	-	-	-	-	
						700	186	-	-	1.96	18.46	-	-	2	-	-	
	Straw	-	17	10	N_2	300	-	-	6.1	1.47	-	-	76.3	8	23.7	94.8	
				60			-	-	9.4	0.79	-	-	33.5	19.1	66.5	36.8	
				10		450	-	-	9.8	0.51	-	25.1	19.4	22.4	80.6	28.5	
				60			16	-	10.1	0.49	-	25.5	15.9	22.9	84.1	27.5	
				10	-	600	-	-	10.9	0.32	-	25.6	8.8	24.5	91.2	25.4	
				60			22	-	11.3	0.28	-	25.1	7.4	25.5	92.4	25.2	
				10		750	-	-	12.1	0.20	-	-	4.2	26.2	95.8	23.7	
				60			-	-	11.9	0.16	-	-	4.1	25.8	95.9	24.4	
Aquatic biomass (AB)	Dry algae	-	17	10	N_2	300	-	-	4.9	1.38	-	-	70.0	46.3	30.0	72.8	
				60			-	-	7.7	1.19	-	-	55.2	55.8	44.8	50.1	
				10		450	-	-	9.1	0.72	-	9.22	27.5	68.6	72.5	28.4	
				60			14	-	9.3	0.61	-	8.68	19.1	71.8	80.9	25.0	
				10	-	600	-	-	11.1	0.41	-	8.29	18.9	72.2	81.1	24.1	
				60			19	-	11.9	0.29	-	8.17	15.7	73.0	84.3	22.9	
				10		750	-	-	12.4	0.21	-	-	10.1	74.8	89.9	21.0	
				60			-	-	12.5	0.19	-	-	3.9	76.4	96.1	19.3	

Table B3 Properties of biochar produced from fast pyrolysis

	Feedstock	Operation conditions				T (℃)	Physical properties		Chemical properties								Reference
		Size (mm)	Heating rate (℃/min-1)	Residence Time (minutes)	Media		SSA (m^2/g)	V_{micro} (cm^3/g)	pH (H_2O)	H/C	O/C	HHV (MJ/kg)	VM (%)	Ash (%)	FC (%)	Yield	
Woody biomass (WD)	Cocoa pod husk	-	-	-	-	450-650	-	-	-	-	-	-	-	10-25	-	-	[219]
	Empty oil palm fruit bunch	-	-	-	-	450-650	-	-	-	-	-	-	-	5	-	-	
						400	-	-	8.1	0,61	-	-	-	1.3	-	31	[211]
						500	-	-	8.1	0,61	-	-	-	2	-	26	
						600	-	-	8.1	0,61	-	-	-	2	-	21	
	Pine	-	-	-	-	400	-	-	8.1	0,61	-	-	-	0.7	-	31	
						500	-	-	8.1	0,61	-	-	-	0.7	-	26	
						600	-	-	8.1	0,61	-	-	-	1	-	21	
	Oak	-	-	-	-	400	-	-	8.1	0,61	-	-	-	0.7	-	31	
						500	-	-	8.1	0,61	-	-	-	3.7	-	26	
						600	-	-	8.1	0,61	-	-	-	1.3	-	21	
	Pine wood	-	-	-	-	450			5.1	0.6	0.24	-	44.65	1.37	52.22	26.6	[220]

										6							
						600			6.5	0.40	0.09	-	19.68	2.05	77.29	15.2	
						800			10.4	0.17	0.03	-	2.61	5.19	91.55	9.5	
	Pitch pine wood chips	-	-	-	-	400	4,8	-	-	-	-	-	-	-	-	-	[205]
						500	-	-	-	-	-	-	-	-	-	14.4	
	Pine sawdust	-	-	-	-	400	-	-	6.35	-	-	-	-	2.2	-	55	
						500	36	0.015	-	-	-	-	-	-	-	-	
						700	65	0.048	9.08	-	-	-	-	7.8	-	-	
						800	-	-	-	-	-	-	-	-	-	17.7	
	Hickory wood	-	-	-	-	450	12.9	-	8	3.83	13.76	-	-	-	-	-	[15]
						600	401	-	9.4	2.69	17.11	-	-	-	-	-	
	Coconut	1	-	4	-	300	4.495	-	7.41	0.61	0.40	-	-	3.76	-	-	[221]
						700	540.63	-	10.53	0.43	0.25	-	-	6.65	-	-	
	Apple tree Branches	-	-	-	-	300	2.39	0.13	7.48	-	-	-	60.77	6.72	32.50	47.94	[149]
						400	7.00	0.52	-	-	-	-	29.85	7.85	62.30	35.49	
						500	37.24	1.58	-	-	-	-	23.19	10.06	66.75	31.73	
						600	108.59	37.87	11.62	-	-	-	14.86	9.40	75.73	28.48	
Animal waste (AW)	Chicken litter	-	-	-	-	620	-	-	-	2.89	1.69	-	-	53.2	-	46	[15]
	Dairy manure	-	-	-	-	350	1.6	-	9.2	7.71	33.51	-	-	24.2	-	54.9	
						700	186.	-	9.9	1.5	7.23	-	-	39.5	-	35	

							5			9							
	Goat manure	- -	- -	- -	- -	400	3.3	-	-	3.98	70.49	-	-	-	-	44,5	
						800	93.5	-	-	1.83	49.77	-	-	-	-	33.8	
	Human manure	-	-	-	-	700	11.1	-	-	4.95	160.16	-	-	62.5	-	30.6	
	Poultry litter	-	-	-	-	350	3.9	-	8.7	7.44	30.53	-	-	30.7	-	54.3	
						700	50.9	-	10.3	4.36	22.88	-	-	46.2	-	36.7	
						350	1.1	-	8.7	8.03	18.66	-	-	35.9	-	72	
						700	9	-	10.3	0.68	-	-	-	52.4	-	44	
	Sow manure	-	-	-	-	500	12.7	-	10.3	3.8	9.06	-	-	59.6	-	46	
	Swine manure	-	-	-	-	350	0.9	-	-	9.51	21.55	-	-	32.5	-	62.3	
	Swine solid	-	-	-	-	350	2.6	-	-	7.3	31.24	-	-	34.8	-	58.1	
						620	-	-	-	3.75	-	-	-	44.7	-	46	
						700	4.1	-	-	1.59	9.07	-	-	52.9	-	36.4	
						0	0.53	-	7.8	1.52	0.41	19.39	73.6	20.9	5.6	-	
						350	0392	-	8.4	1.14	0.16	21.12	49.8	32.5	17.7	-	
						700	4.11	-	9.5	0.20	0.07	15.07	13.4	52.9	33.8	-	
	Turkey litter	-	-	-	-	700	66.7	-	-	2.01	12.95	-	-	49.9	-	39.9	

Biosolids sludge (BS)	Sewage sludge	-	-	-	-	550	-	-	6.81	-	-	-	4.29	70.5	25.2	-	[222]
	Sludge biochar	3.5	50	-	-	300	-	-	5.32	-	-	-	33.8	52.8	9.1	72.3	[223]
		-	-	-	-	400	-	-	4.87	-	-	-	25.7	63.3	6.8	63.7	
		-	-	-	-	500	-	-	7.27	-	-	-	20.7	68.2	7.6	57.9	
		-	-	-	-	700	-	-	12	-	-	-	15.8	72.5	8.3	52.4	
	Sewage sludge	-	-	-	-	400	0.1	0.0014	7.7	-	-	-	21.3	52.0	26.7	-	[224]
		-	-	-	-	450	2.9	0.0036	8.2	-	-	-	17.3	55.6	27.1	-	
		-	-	-	-	500	3.2	0.0017	9.0	-	-	-	14.2	57.6	28.2	-	
		-	-	-	-	550	13.3	0.0066	9.9	-	-	-	13.0	58.5	28.5	-	
Herbaceous (HB)	Safflower seed press cake	1.8	10	60	N2	400	2.67	0.0050	8.18	0.71	0.26	28.15	25.20	7.50	67.3	34.18	[225]
						450	3.33	0.0053	9.13	0.59	0.24	28.86	20.0	8.20	71.80	-	
						500	4.23	0.0067	9.44	0.50	0.23	29.39	16.50	8.50	75.00	-	
						550	3.78	0.0060	9.67	0.44	0.21	29.31	13.90	8.90	77.20	-	
						600	3.41	0.0064	9.89	0.38	0.20	30.06	11.60	9.20	79.20	26.06	
		1.8	30	60	N2	400	2.26	0.0036	7.59	0.60	0.26	28.51	21.40	8.40	70.20	-	
						450	2.92	0.0046	8.71	0.55	0.25	28.98	18.70	8.50	72.80	-	
						500	3.98	0.0063	9.52	0.49	0.23	29.59	15.20	8.60	76.20	-	
						550	3.26	0.0041	9.70	0.45	0.22	29.97	12.30	9.10	78.60	-	

						600	2.85	0.0059	10.15	0.38	0.21	30.7	10.80	9.30	79.90	-	
		1.8	50	60	N_2	400	1.89	0.0029	8.07	0.64	0.26	28.77	19.80	8.50	71.7	29.70	
						450	2.71	0.0043	8.46	0.54	0.25	29.2	17.40	8.60	74.0	-	
						500	3.64	0.0057	9.30	0.48	0.23	29.73	14.30	8.70	77.0	-	
						550	2.83	0.0045	9.56	0.47	0.22	30.12	11.40	9.10	79.5	-	
						600	2.47	0.0039	9.77	0.43	0.21	30.27	9.80	9.50	80.7	24.8	
	Maize stover	-	-	-	-	450-650	-	-	-	-	-	-	-	9.15	-	-	[9]
	Sorghum stover	-	-	-	-	450-650	-	-	-	-	-	-	-	4	-	-	
	Switchgrass	-	-	-	-	450	-	-	9.1	0.62	0.17	-	26.43	13.44	58.38	31.3	[220]
						600	-	-	10.6	0.42	0.06	-	11.15	19.43	68.54	16.9	
						800	-	-	11.2	0.19	0.05	-	3.26	21.52	74.69	11.4	

Table B4 Properties of biochar produced from gasification

Feedstock		Gasifying agent	Residence Time (min)	T (°C)	Physical properties		Chemical properties								Reference
					SSA (m^2/g)	V_{micro} (cm^3/g)	pH (H_2O)	H/C	O/C	HHV (MJ/kg)	VM (%)	Ash (%)	FC (%)	Yield (%)	
Woody biomass (WD)	Wood Chips	Air	-	650	78	0.08	-	-	-	-	-	49.52	-	-	[226]
				800	281	0.13	-	-	-	-	-	8.68	-	-	
	Ponde	-	-	-	296	-	10.	0.0	0.0	-	-	-	-	-	[227]

	rosa pine wood						2	81	12						
					233	-	9.3	0.089	0.001	-	-	-	-	-	
	Beech	-	-	670	-	-	11	-	-	27.5	12.3	17.5	70.2	-	[228]
	Wood	-	-	670	-	-	12	-	-	24.4	13.3	22.5	64.2	-	
	Coconut shells	N_2	60	750	631.52	0.21	-	-	-	-	-	3.9	-	-	[229]
			120	750	772.30	0.26	-	-	-	-	-	7.7	-	-	
			180	750	884.00	0.30	-	-	-	-	-	6.0	-	-	
			60	850	1041.83	0.34	-	-	-	-	-	8.2	-	-	
			120	850	1032.60	0.38	-	-	-	-	-	7.1	-	-	
	Oil palm shells	N_2	60	750	490.00	0.17	-	-	-	-	-	4.4	-	-	
			120	750	504.20	0.18	-	-	-	-	-	4.6	-	-	
			180	750	529.90	0.19	-	-	-	-	-	4.8	-	-	
			60	850	667.40	0.25	-	-	-	-	-	4.9	-	-	
			120	850	776.00	0.26	-	-	-	-	-	5.6	-	-	
			180	850	931.00	0.32	-	-	-	-	-	8.3	-	-	
	Wood chips	CO_2	-	731-862	467.1	0.172	-	-	-	-	15.34	23.68	60.95	-	[230]
				710-916	748.5	0.287.	-	-	-	-	9.63	13.29	77.01	-	
Animal waste (AW)	chicken manure	air	-	750	-	12.3	-	1.7	0.8	-	-	86	17	-	[231]
		steam	-	750	-	-	-	-	-	-	-	-	78	-	
		air	-	750	-	-	-	-	-	-	-	-	86	-	
Biosolids sludge (BS)	Waste sludge	Steam	120	750	-	-	-	-	-	-	-	-	-	21.35	[232]
				850	-	-	-	-	-	-	-	-	-	32.80	
				950	-	-	-	-	-	-	-	-	-	52.22	
Herbaceous	Switchgras	N_2	240	850	260	-	9.6	0.082	0.014	-	-	-	-	-	[227]

(HB)		-	-	850	188	-	10.8	0.060	0.010	-	-	-	-	-	
	Corn stover	N_2	240	850	196	-	10.4	0.065	0.01	-	-	-	-	-	
		-	-	-	176	-	10.0	0.060	0.008	-	-	-	-	-	
	Switchgrass	-	-	730	-	-	-	-	-	-	-	-	23.9	-	[231]
				760	-	-	-	-	-	-	-	-	31.4	-	
	Green house waste	Steam	-	600	87	0.038	12	-	-	-	-	25	-	-	
		Air	-	600	159	0.069	9.9	-	-	-	-	19	-	-	
		Steam	-	750	251	0.108	11.6	-	-	-	-	27	-	-	
		Air	-	750	299	0.129	10.6	-	-	-	-	25	-	-	
	Corn stover	-	-	700	-	-	-	-	-	-	-	-	-	95.50	[228]
	Bamboo guadua	N_2	60	750	544.97	0.18	-	-	-	-	-	23.6	-	-	[233]
			120	750	648.20	0.21	-	-	-	-	-	24.5	-	-	
			180	750	605.41	0.20	-	-	-	-	-	24.8	-	-	
			60	850	807.70	0.24	-	-	-	-	-	31.5	-	-	
			120	850	723.59	0.21	-	-	-	-	-	44.0	-	-	
			180	850	-	-	-	-	-	-	-	57.9	-	-	

B5 Modifications of biochar properties

Modifications methods		Change of biochar properties			Modification Effects	Reference
		Specific Surface Area (m2/g)	Pore Volume (cm3/g)	C %		
Chemical methods	Impregnated into $AlCl_3$ solutions for 6 h and dried at 80 °C for 48 h.	From 212.58 to 418.14	from 0.077 to 0.056	from 88.63 to 39.10	The carbon content significantly decreased, while SSA significantly increased with the metal content of the biochar.	[234]
	5% H_3PO_4 at 70–80 °C for 2 h under stirring before pyrolysis	from 199 to 557	from 0.026 to 0.22	-	The H_3PO_4 modification enhanced SSA and pore size significantly.	[235]
	Immersed in H_3PO_4	from 227.56	from 0.07	-		[236]

	solution for 24 h at 25 °C.	to 372.21	to 0.14			
	Mixed with Na_2S or KOH solution and stirred for 4 h.	from 32.85 to 59.23	-	-	Chemical modification can effectively increase SSA, which can further increase the sorption capacity.	[31]
	KOH, 60℃, 2 h	from 18 to 783	-	-		[237]
	KOH, 700 °C, 1 h	from 140 to 772	-	-		
	KOH at ambient temperature (25 °C)	from 0.13 to 207	-	-		[187]
	NaOH: biochar=8:1, 2h	From 28.1317 to 115.494 $m^2\cdot g^{-1}$	From 0.03125 to 0.19143 $cm^3\cdot g^{-1}$	-		[238]
	NaOH:biochar=2:1 (800 ℃)	from 0.583 to 1470.266 $m^2\cdot g^{-1}$	0.01 to 0.705 $cm^3\cdot g^{-1}$	-		[163]
	$ZnCl_2$:biochar=2:1 (800 ℃)	from 0.583 to 1067.902 $m^2\cdot g^{-1}$	from 0.01 to 0.511	-		[163]
	$ZnCl_2$:biochar=1:3, 1:1, 3:1 (600 ℃)	From 289.2 to 319.4, 365.6, and 371$m^2\cdot g^{-1}$, respectivly	From 0.143, 0.163, 0.227, and 0.230 $cm^3\cdot g^{-1}$, respectively	-		[239]
	$ZnCl_2$:biochar=4:1 (900 ℃)	From 14.14 to 801.5$m^2\cdot g^{-1}$	-	-		[197]
Physical methods	heated to 700–850 ℃ for 1–7 h	from 220 to 1018	from 0.13 to 0.21	-	Enhanced the catalytic activity due to the increases of SSA and mesopore volume.	[240]
	Heated to 900 °C by microwave, for 75 min,	from 702 To 2079	from 0.53 to 1.212	-		[108]
	steam activation	from 496 to 516	from 0.27 to to 0.08	-	Increased SSA and pore size.	[162]
	Heated to 800 °C using steam for 15 min	from 227 to 1365	from 0.17 to 1.2	-		[166]
	Heating Almond tree pruning to 850 °C using steam for 30 min	from 204 to 1080	from 0.118 to 0.95	-		[241]
	Heating Almond shell to 850 °C using steam for 30 min	from 42 to 601	from 0.094 to 0.375	-		
	Heating Olive stone to 850 °C using steam for 30 min	from 53 to 813	from 0.036 to 0.555	-		
	CO2 treatment	from 5–12 to 60	-	-		[242]
	Using steam to heat at 750 °C	from 429 (0.5 h) to 621 (1 h)	-	-	The pore volume and SSA were proportional while the total acidity was inversely proportional to the heating temperature.	[165]
	Heated to 750 or 920 °C; in CO_2/N_2 (mol%:10/90%) for 0.5h	from 435 (750 °C) to 687 (920 °C)	from 0.18 (750 °C) to 0.30 (920 °C)	-		
	H2SO4 at 180, 280, or 380 °C; N2; 48 h	from 5.3 (180 °C) to 18.7	from 5.4 (180 °C) to 29.6	from 4.3 (180 °C) to 2.6		[243]

		(280 °C) to 23.4 (380 °C)	(280 °C) to 37.2 (380 °C)	(280 °C) to 2.2 (380 °C)		
	Heated to 300 °C to 500°C in N_2 for 4 h	from 13 to 16	from 0.02 to 0.03	-		[244]

Appendix C

Yield	
AW	(3.5998 e-04)x2 + (-0.4237)x + (163.6182)
BS	(2.5938 e-04)x2 + (-0.3275)x + (141.9240)
HB	(3.3097 e-04)x2 + (-0.4334)x + (160.8863)
WD	(2.9657 e-04)x2 + (-0.3946)x + (149.3555)
Specific surface area	
AW	(-7.1626e-07)x3 + (1.4159e-03)x2 + (-0.6237)x + (97.3073)
BS	(-3.6831e-06)x3 + (6.6890e-03)x2 + (-3.5696)x + (591.0094)
HB	(4.0566e-06)x3 + (-3.2001e-03)x2 + (0.6022)x + (41.9945)
WD	(-5.2283e-06)x3 + (1.0499e-02)x2 + (-5.3434)x + (861.0902)
pH	
AW	(2.0508e-06)x2 + (2.1193 e-03)x + (7.8873)
BS	(1.3227e-05)x2 + (-5.7155 e-03)x + (7.8918)
HB	(1.0658e-06)x^2 + (5.7810 e-03)x + (6.7043)
WD	(1.7464e-06)x2 + (4.8364 e-03)x + (5.4733)
H/C	
AW	(-5.9163e-07)x2 +(5.1385 e-04)x + (-3.7862e-2)
BS	(6.6298e-07)x2 +(-7.8740 e-04)x + (0.2453)
HB	(-1.7407e-07)x2 +(1.1662 e-04)x + (2.6995e-2)
WD	(-2.0091e-07)x2 +(1.0335 e-04)x + (6.0484e-2)
O/C	
AW	(-1.5668e-08)x3 + (2.4600e-05)x2 + (-1.3091e-2)x + (2.5758)
BS	(-5.0711e-10)x3 + (1.3863e-06)x2 + (-1.4986e-3)x + (0.6491)
HB	(-6.0043e-09)x3 + (1.0679e-05)x2 + (-6.7090e-3)x + (1.6233)
WD	(-8.0591e-09)x3 + (1.3904e-05)x2 + (-8.2896e-3)x + (1.8546)
Higher Heating Value	
AW	(-7.9188e-06)x2 + (3.3163e-3)x + (21.1897)
BS	(1.2366e-05)x2 + (-6.7986e-4)x + (24.8202)
HB	(-2.4748e-05)x2 + (4.2966e-2)x + (11.9773)
WD	(-4.4655e-05)x2 + (6.4086e-02)x + (9.4117)
Volatile matter	
AW	(1.5584e-04)x2 + (-0.2470)x + (120.6111)
BS	(2.9131e-04)x2 + (-0.3837)x + (139.0015)
HB	(2.7676e-04)x2 + (-0.3878)x + (145.8539)
WD	(1.6299e-04)x2 + (-0.2761)x + (125.7159)
Ash	
AW	(-1.5058e-04)x2 + (0.2123)x + (-23.6852)
BS	(-1.2157e-05)x2 + (6.6494e-02)x + (5.2750)
HB	(1.0101e-04)x2 + (-5.5933e-02)x + (25.9766)
WD	(2.4210e-05)x2 + (1.2412e-02)x + (-0.4586)
Fixed carbon	
AW	(1.7783e-04)x2 + (-0.1401)x + (43.1360)
BS	(2.3908e-05)x2 + (6.5476e-2)x + (-0.9765)
HB	(-2.9973e-04)x2 + (0.4115)x + (-59.4818)
WD	(-1.0881e-04)x2 + (0.2084)x + (-17.7345)

Author Statement

Yanqi Xie: Investigation, Writing

Hailong Li: Conceptualization, Methodology, Visualization, Supervision, Writing - Review & Editing, Project administration

Lara Carvalho: Investigation, Writing - Review & Editing

Lena Johansson Westholm: Investigation, Writing

Liang Wang: Investigation, Writing - Review & Editing

Eva Thorin: Investigation, Writing

Zhixin Yu: Investigation, Writing

Xinhai Yu: Investigation, Writing

Øyvind Skreiberg,. Review & Editing

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Highlights:

- Requirements on the properties of biochar for different applications have been identified and summarized.
- The correlation between biochar properties and requirements of different applications have been reviewed.
- Recommendations are given regarding selection and improving production processes and feedstock for producing biochar designed towards certain applications.