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Biochar from waste biomass, its fundamentals, engineering aspects, and potential applications: an overview

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ABSTRACT

Environmental pollution control in the growing world is a challenging task for all the countries in order to keep the environmental sustainability. Biochar, a processed carbon material, draws a significant attention in the field of environmental remediation, as of its active functional groups that help remove environmental pollutants to a level insignificant to cause hazardous effects. As such, there is an increasing interest developed to promote highly productive biochar for exploring environmental engineering aspects. There is limited comprehensive literature available for understanding biochar science and its potential applications under an umbrella. This review was set to fill this knowledge gap by discussing key points related to biochar, its novel engineering aspects and potential environmental applications. Therefore, this overview tends to summarize and discuss biochar, its fundamentals, engineering aspects commonly used modifications and the potential applications of biochar in water treatment with an intention of addressing the importance of biochar for environmental remediation process. This overview will be useful for researchers, policy-makers and stakeholders to plan and review relevant scientific works in order to produce customized biochar for future environmental applications.

Key words: engineered biochar, environmental remediation, hydrochar, pollution control, pyrolysis

HIGHLIGHTS

- Comprehensive summary of new methods used for engineered biochar production.
- Discussion about the functional properties of engineered biochar.
- New insights into the use of engineered biochar for the removal of pollutants.
- Mechanism of pollutant removal by engineered biochar.

GRAPHICAL ABSTRACT
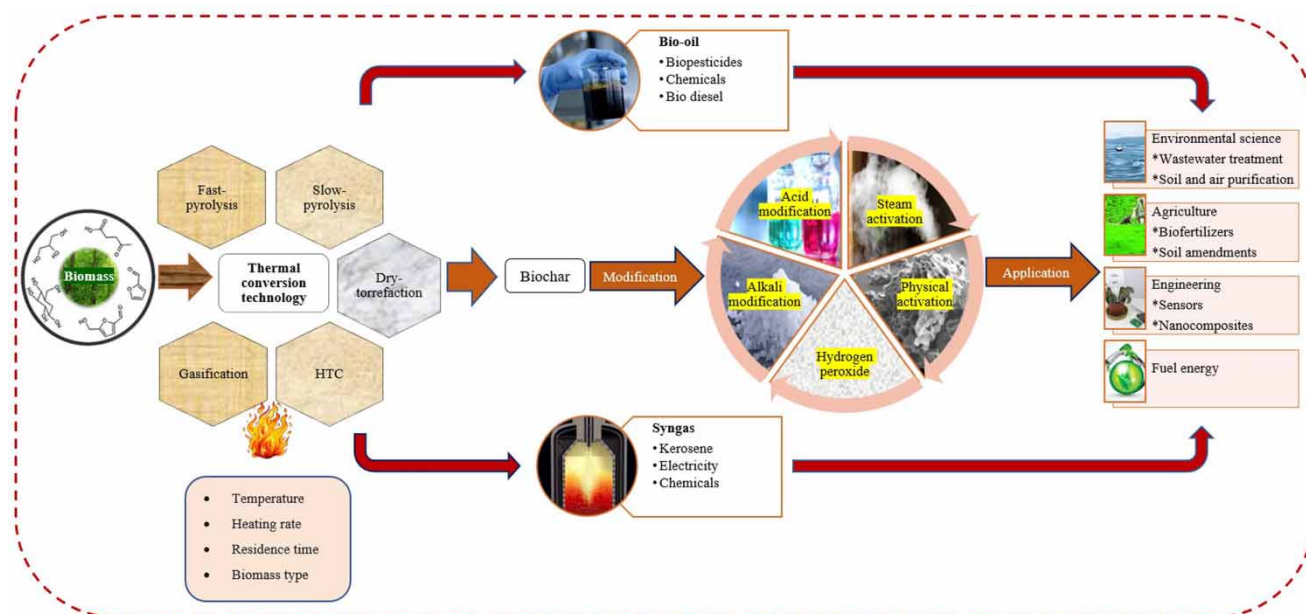
1. INTRODUCTION

World population is growing at a faster rate, which creates a significant demand for existing natural resources. Furthermore, many environmental problems are created by such growth and industrial revolution. It was reported that the population in 2022 had been around 7.9 billion, and it is predicted to reach 9.6 billion by the year 2050. The process of environmental remediation has benefited greatly from the science of biochar. Many research activities are being undertaken to increase the potential use of biochar for the removal of contaminants. The biochar was originated in the Amazon region where the carbon-rich earth was created through char techniques (Zech *et al.* 2015). This attempt was made because char was considered to be an excellent source of soil amendment for soil fertility and sustainability.

Furthermore, its potential has been recognized as an efficient tool for environmental management (Liu *et al.* 2015). Biochar science is a newly constructed science and grows faster as of its potential benefits. Many researchers have developed various definitions for biochar. However, the core concept in each definition reflects the same meaning. According to Lehmann and Joseph, it is defined as a carbon-rich product when biomass is heated in a closed system under little or unavailable oxygen (Lehmann & Joseph 2009). It has got another definition: biomass that has been pyrolyzed in a zero or low oxygen environment applied to soil at a specific site that is expected to sequester carbon so as to improve soil functions under current and future management while avoiding short-term and long-term detrimental effects to the wider environment, human and animal health (Verheijen *et al.* 2009).

According to the International Biochar Initiative's (IBI) standard definition, biochar is a solid substance created when biomass is thermochemically converted in a close environment with limited oxygen. It is vital to understand the differences between charcoal and biochar. The primary difference between these two terms is determined in how they are ultimately used. In contrast to biochar, which is primarily used for carbon sequestration and environmental management, charcoal is a carbon material used to produce fuel and energy (Kołodyńska *et al.* 2012). It has wide range of applications in environmental management. Biochar is produced by number of distinct methods. The term 'hydrochar' is very closely related to biochar, but it defers from biochar as of its specific production configurations. Biochar is produced by dry carbonization, whereas hydrochar is produced by hydrothermal carbonization (HTC) in the presence of hot compressed water.

These two chars differ from each other because of their specific functional groups (Libra *et al.* 2011; Wiedner *et al.* 2013). Biochar consists of wide range of surface functional groups that are responsible for the removal of pollutants present in soil and water. Biochar is used mainly in areas such as soil management, waste management, climate science and energy sector (Kambo & Dutta 2015). The chemical and physical properties of biochar are mainly determined by the nature of the

feedstock, condition of the thermal processing, reaction time, vapor pressure, arrangement of vessel and reaction temperature (Demirbaş 2001). The pH of biochar is normally neutral to alkaline; however, acid biochar has also been reported (Mojiri *et al.* 2020). In general, alkaline biochars are used for the reclamation of acid soils towards positive fertility range (Yu *et al.* 2013).

Furthermore, its application to soil considerably enhances seed germination, plant growth and development, and crop yield (Beesley *et al.* 2010). Biochar can be applied together with organic and inorganic fertilizers to the soil to increase the crop yield since it drastically improves symbiotic organisms in the soil (Verheijen *et al.* 2009). However, biochar application to soil stimulates decomposition of soil native carbon by inducing soil microbes (Ahmad *et al.* 2014) and chemical hydrolysis. Biochar is widely used in the management of waste materials that are originated from plant and animal residues. The production of biochar from such waste materials are cost-effective and beneficial as far as the energy sector and climate mitigation targets are concerned (Brick *et al.* 2010). Many residues such as municipal solid wastes, food processing waste, animal residue, paper mill waste and forestry waste, are used to produce biochar under oxygen limited conditions (Mosier *et al.* 2005). Moreover, a study employing sugarcane bagasse (SB) has emphasized important discoveries, such as the exceptional adsorption capabilities of activated carbon, which is generated at 400 °C for carbonization and 900 °C for activation, and it had an amazing surface area of 589.73 m^2/g. These findings advance knowledge in using agricultural waste, like SB, to produce efficient adsorbents in a sustainable manner (Somyanonthanakun *et al.* 2016).

However, it is vital to handle the biochar with care in situations in which char is processed from sources of heavy metals, sludge and municipal solid waste (Lu *et al.* 2012). Converting biomass into biochar is the best way to sequester carbon so as to mitigate climate change impacts (Lehmann *et al.* 2011). Biochar can lower nitrous oxide emissions from soil through both biotic and abiotic processes (Choppala *et al.* 2012). In addition, production of biochar from waste biomass by the pyrolysis process leads to bioenergy production, which can be used to substitute fossil fuel energy with low CO_2 emissions into environment (Chatterjee *et al.* 2020). The process of bioenergy production is influenced by pyrolysis conditions in which fast pyrolysis yields more liquid fuels compared to slow pyrolysis that yields greater char yield in the total end product mass (Demirbaş 2001). Moreover, discharge of industrial pollutants into water bodies creates significant environmental impact. Anthropogenic activities are primarily responsible for the accumulation of organic and inorganic contaminants.

Hence, vast attention is being paid by researchers to remediate contaminated water by reducing the bioavailability of contaminants and decrease the accumulation of heavy metals along food chain. Biochar is emerging as an aid in reducing the bioavailability of pollutants. It is therefore important to explore the research in the field of biochar science for the future world applications (Libra *et al.* 2011). Many modification techniques are incorporated in the research wing of biochar science to improve the functional properties of biochar. These processes lead to produce biochar with complex and heterogeneous physical and chemical composition that is responsible for an ideal platform for contaminant removal via sorption (Zheng *et al.* 2010). However, very limited pieces of information are available for understanding technical aspects of biochar under one umbrella.

Therefore, this review paper tends to give an overview of currently available biochar production methods, recently focused biochar modification strategies to enhance sorptive capacities for better remediation and the potential applications of biochar for pollution control based on recent literature available. Moreover, efforts have been made to address proper comparisons in the production process, modification techniques and application methods. Hence, this timely needed review would help to facilitate researchers to go for better research implementations in customized biochar production for future applications.

1.1. Feedstock for biochar production

There are various feed stocks used to produce biochar by different methods. However, the end product quality is totally dependent on the conditions of processing method and the nature of feedstock. The term biomass plays a key role in the production process of biochar. It is a lignocellulosic material obtained from wood and other organic residuals. However, other waste materials such as organic solid wastes and animal excreta, are also put under the concept 'biomass' in the field of biochar science (Akdeniz 2019). Biomass usually consists of hemicellulose, cellulose and lignin in various proportions depending on the nature of feedstock. It is, at present, considered widely as one of the emerging renewable energy sources to recover energy by the systematic thermochemical induction in an arranged vessel. This conversion yields fuel oil, solid material (char) and gases. The production of different feedstock for the accumulation of good quality biochar for distinct applications in energy sector and environmental remediation is becoming popular (Wang & Wang 2019). Figure 1 illustrates
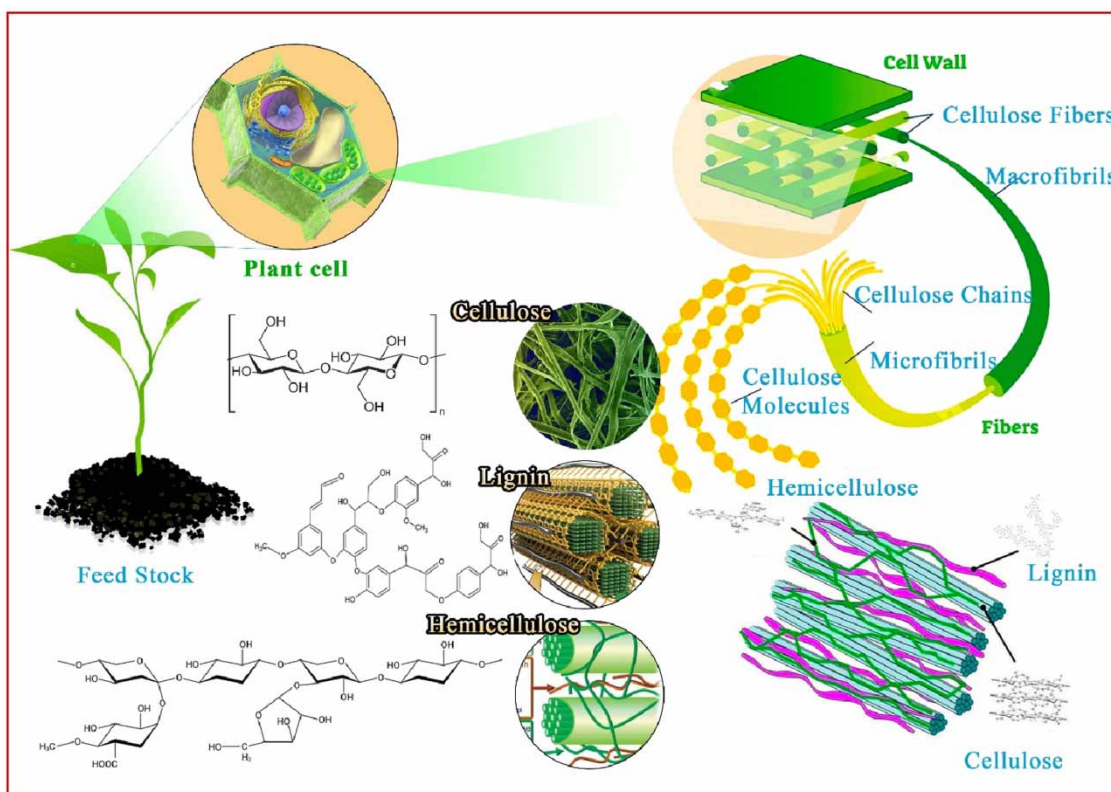
Figure 1 | Biomass structure.

the scientific display of plant biomass material. It is obvious from the Figure 1 that biomass materials have various structural elements, which have specific degrees of thermal stabilities.

The structure of the biomass is very complicated, and the compounds, cellulose, hemicellulose and lignin, are meshed strongly with each other by chemically enhanced bonding forces that make its structure rigid to be deformed. Therefore, selection of appropriate biomass is very important to have high biochar yield at the end of the production process. The efficiency of biomass, on this conversion into biochar, is strongly influenced by its heating value, fibrous nature, bulk density, moisture content, earth metallic content and alkali content (Kambo & Dutta 2015). Hence, care must be taken while selecting the biomass for production of biochar. Table 1 describes the properties of lignocellulosic composition of biochar. The composition of lignocellulosic components in the biomass plays a crucial role in determining the ultimate characteristics of biochar. Biomass is usually divided into two broad groups: wet biomass and dry biomass, depending on their initial moisture content. Biomass that is available in freshly harvested materials has high moisture content of greater than 30% (wet basis), while agricultural residues and few woody spices typically have low moisture content of lower than 30% (wet basis) at their harvesting time (Suliman *et al.* 2016).

This initial moisture content is crucial as far as biochar production is concerned. It is not economical to use wet biomass for the biochar production as it requires energy intensive steps to reduce its initial moisture content to a level suitable for reasonable char yield (Kołodyńska *et al.* 2012). Biomass species are now being grown deliberately with an intention of making feedstock available for bioenergy production (McKendry 2002). These purposely grown tree species have low moisture content (10% wet basis) at the time of harvesting compared to other woody species. The ash content of biomass species grown is significantly affected by harvesting time. That may impart combustion behaviors as well (Senelwa & Sims 1999).

Furthermore, the synthesis of biochar from waste biomass materials, namely forest residue, animal excreta, treated sludge and municipal solid waste, are practically viable since such feedstock concerned have no economic value with no competition for land space for their growth and development. However, it is important to pay attention on the use of waste biomass for biochar production. For example, waste biomass left on the soil surface has a potential to improve the soil

Table 1 | Properties of lignocellulosic composition of biochar (Kambo & Dutta 2015)

Characteristics/ Application	Compound		
	Cellulose	Hemicellulose	Lignin
Molecular formula	$(C_6H_{10}O_5)_n$	$C_5H_{10}O_5$	$C_9H_{10}O_2$ $C_{10}H_{12}O_3$ $C_{11}H_{14}O_4$
Hydrophobicity	Medium	Low	High
Thermal stability	It can be hydrolysed in sub-critical water at around 180 °C, and standard condition is between 300 and 400 °C	Under standard conditions, it may be pyrolyzed in water at around 160 °C.	Thermally more stable
Solubility in water	Non-soluble	Partially soluble	Hydrolysis starts at 600 °C
Application	Paper, biofuel and textile	Animal feed and food packaging	Adhesive manufacturing and bioenergy

properties for better crop yield. Overuse of these materials, may end up with harmful effects as far as soil fertility is concerned. Therefore, producers, policy-makers and researchers connected to this broad area of biochar science should have clear vision on the feedstock production, selection, harvesting and the use prior to make the final arrangement for keeping natural ecological balance with expected product yield.

2. CRITICAL COMPARISON OF TECHNOLOGIES USED TO CONVERT BIOMASS INTO BIOCHAR

A range of conversion techniques have been developed to efficiently convert biomass into biochar. Thermal methods are in use commonly in the conversion process of biomass into biochar, although biological treatments such as anaerobic digestion, hydrolysis and fermentation, are available to carry out the same task. Combustion, pyrolysis, HTC, torrefaction and gasification are thermal treatments used to convert biomass into biochar and fuel. A comprehensive summary of thermal treatments for biochar production is depicted in Table 2 for better understanding. Broad attention is given in this chapter on thermochemical conversion technologies used to produce biochar and biofuel with possible comparisons. The yield of each thermal process defers as of the differences in pre-treatments and post-processing requirements, like sizing, drying, cooling and condensation (Mosier *et al.* 2005). The products obtained from the treatments like gasification and dry torrefaction are similar to biochar; however, they are not regarded as biochar because of their poor functional properties compared to biochar (Kambo & Dutta 2015).

2.1. Biomass pyrolysis

Biomass pyrolysis results in the thermochemical decomposition of biomass at temperatures ranging from 300 to 900 °C in the presence of limited or no oxygen (Kazemi Shariat Panahi *et al.* 2020; Yaashikaa *et al.* 2020). Moreover, to produce a very high carbon content of more than 95%, treatment temperatures above-average 700 °C might be required. However, this is possible with woody feedstock, but it is difficult with agricultural waste and other materials that produce ash at low temperatures. As a result, they are usually not handled above 700 °C (Weber & Quicker 2018). The pyrolysis process is effective as it converts waste biomass into valuable products like biochar, bio-oil and syngas (Yaashikaa *et al.* 2020). It is usually divided into three

Table 2 | Comparison of biochar produced via various thermal conversion technologies (Kambo & Dutta 2015)

Pre-treatment method	Operating temperature (°C)	Residence time	Heating rate	Typical product yield (%)		
				Solid	Liquid	Gas
Fast pyrolysis	400–500	1–5 s	1,000 °C/s	10–15	60–70	15–20
Slow pyrolysis	300–650	5 min–12 h	10–30 °C/min	25–35	20–30	25–35
Gasification	600–1,200	10–20 s	50–100 °C/s	<10	<5	>85
Dry torrefaction	200–300	30 min–4 h	10–15 °C/min	60–80	–	20–40
HTC	180–260	5 min–12 h	5–10 °C/min	45–70	5–25	2–5

groups: fast pyrolysis, intermediate pyrolysis and slow pyrolysis, depending on the residence time, heating rate and reaction temperature.

Fast pyrolysis is used to produce bio-oil as of its short residence time of less than 2 s and high bio-oil yield of 75% (Mohan et al. 2006). Intermediate and slow pyrolysis processes are set with long residence time to yield biochar from biomass. Pyrolysis covers a range of thermal decomposition processes, and it is difficult to define preciously. In the absence of air, biomass is slowly heated to around 500 °C. Vapor residence periods range between 5 and 30 min. Slow pyrolysis produces less vapor than fast pyrolysis. When compared to other procedures, slow pyrolysis typically generates 25–35% char (Brownsort 2009). Low operating temperatures and slow heating rates favor high solid yield in the slow pyrolysis process (Karaosmanoglu et al. 1999). Figure 2 shows the fundamental concept behind pyrolysis process. It is clear from the Figure 2 that the pyrolysis process of biomass at the end of the process yields biochar and bio-oil.

2.2. Gasification

Gasification is totally different from the pyrolysis process because of its high reaction temperature compared to pyrolysis temperature. It is the process of partial decomposition of biomass at high temperatures (600–1,200 °C) for short residence time of 10–20 s (Tomczyk et al. 2020). A gas-fuel that is produced from the gasification process can be used to produce heat or electricity. The final composition of the end product is controlled by reaction temperature, residence time, particle size and gas composition. This process technically yields no biochar since most of the materials are converted into gas and ash during this process. However, it may yield less than 10% biochar at the end depending on the process conditions (Xie et al. 2015). The presence of toxic compounds such as alkali and alkaline earth metals and polyaromatic hydrocarbons are common as of its higher reaction temperature (Guan et al. 2016). Hence, it is not at all possible to use such solid material for environmental remediation (Sivula et al. 2012). Furthermore, the biochar from the gasification process does not meet the IBI guidelines. Hence, no attempt has been taken in this overview to compare the char produced from gasification with chars produced by pyrolysis and HTC.

2.3. Torrefaction

Torrefaction reaction is just the beginning of the pyrolysis process. It occurs between 250 and 280 °C at low heating rates. It yields a brown or black product with low mechanical strength. However, the torrefaction process generates wood yields up to 84% with the maximum energy yield of 90% (Antal & Grønli 2003; Kambo & Dutta 2015). Torrefaction increases biomass energy density; decreases weight; improves hydrophobicity; promotes commercial usage of wood by minimizing transportation problems. This process has received great interest in the world of bioenergy since it is a critical pre-processing step
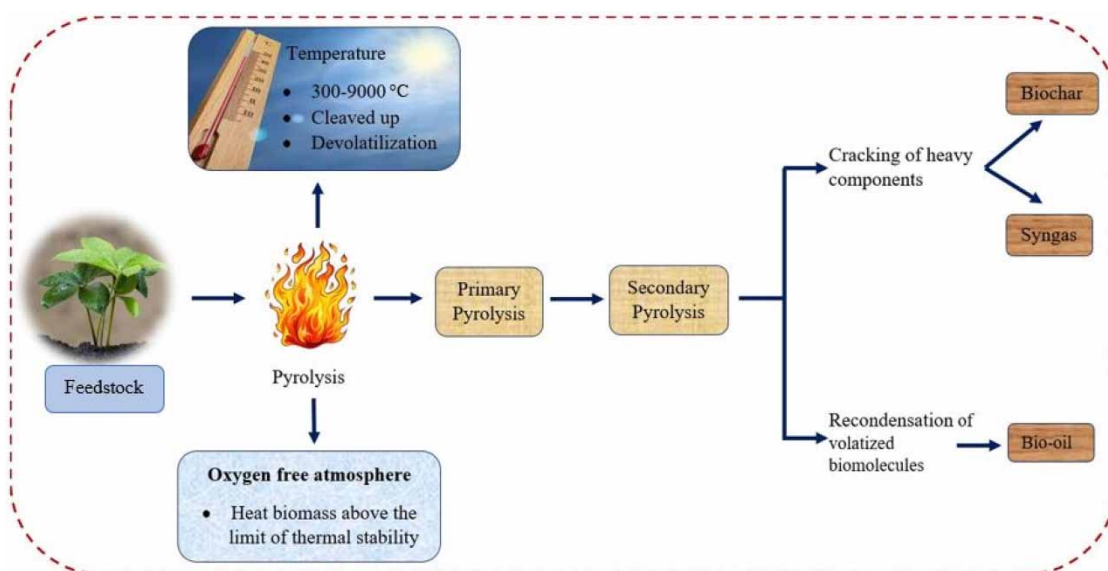

Figure 2 | Process of pyrolysis.

for increasing the physiochemical characteristics of biomass (Bergman *et al.* 2005). However, the solid product produced from this process cannot be treated as biochar since such end product still contains some original compounds of biomass. Its properties lie between the properties of biomass and biochar. Hence, this end product cannot be used for energy recovery upon requirements.

2.4. Hydrothermal carbonization

This process is used to produce char–water–slurry at high temperature and pressure in the presence hot, compressed water (Lynam *et al.* 2011). This process is also known as wet torrefaction as of the low reaction temperature and presence of water. HTC is performed at temperatures ranging from 180 to 260 °C with an elevated pressure of 2–5 MPa. This process has been drawing vast attention from bioenergy sector and the window of environmental remediation since it produces important chemicals together with production of liquid and gaseous fuel (Mumme *et al.* 2011). The temperature profile of the reactor in which this reaction is carried out is responsible for phase differentiation of reactions. HTC occurs at the end point temperature below 260 °C, while hydrothermal liquefaction (HTL) and hydrothermal vaporization (HTV) do happen above 260 °C. The main objective of HTL and HTV is to produce liquid and gaseous fuel; however, it is not to produce biochar from biomass residues.

In addition, HTC has a number of benefits over pyrolysis of biomass, which is significantly impacted by the initial moisture content of the biomass. As HTC is performed in the presence of water, no attention is needed to reduce the initial moisture content of biomass to levels required to increase the efficiency of pyrolysis. This makes the HTC process effective in terms of economic concerns (Mani *et al.* 2006). The processing configurations and arrangements of vessels do crucially influence its end products such as solid, liquid, and gas. However, much emphasize is given to its reaction temperature, which is the controlling key of the entire process. The HTC process produces solid end product called 'hydrochar' with the production yield of around 40–70% (Kambo & Dutta 2014). However, the intensification of pressure and temperature regimes can be regulated by addition of some catalysts (Gao *et al.* 2020).

Hydrochar produced by HTC needs serious mechanical treatments to reduce its moisture content and improve its functional properties. The moisture content of hydrochar can be reduced to 70–75% by mechanical processing soon after production. It is further important to incorporate appropriate thermal techniques if further moisture reduction is expected. Disintegration of hydrochar is less energy intensive compared to biochar as of its high moisture content (He *et al.* 2013). The strong water affinity of these pulverized hydrochars is due to the high degree of aromatization and the high number of oxygen containing functional groups (Libra *et al.* 2011). Furthermore, hydrochar has good properties and production merit compared to biochar because of its economical pathway and reliable mechanical configurations. However, there is a debate about hydrochar production to replace for environmental remediation. Therefore, final selection of hydrochar production for environmental remediation must be made with care. Hence, a brief comparison has been made in Table 3 for better understanding of both HTC and pyrolysis, which can be used for various environmental applications.

Table 3 | Comparison of HTC and pyrolysis process

Parameter	Surface area and porosity		Mass yield		Degree of de-hydration and de-carbonization	
	Pyrolysis	HTC	Pyrolysis	HTC	Pyrolysis	HTC
High reaction temperature	Increasing the temperature beyond 500 °C has a negative impact on the properties	Typically increase up to 230 °C and further increase shows negative results	Decrease	Decrease	Increase	Increase
Reaction residence time	Increase	Decrease	Decrease	Decrease	Increase	Increase
Moisture content of feedstock	Supply of energy is required for drying	Not affected	Decrease	Not affected	–	Initial reaction is initiated by hydrolysis
Pre-processing	Increase with reduction in time	Effect is much less	Decrease	Decrease	Increase	–
Pressure	Decrease	Decrease	Increase	Increase	–	–

2.5. Comparisons of biochar produced by various processes

It is important to develop an overall comparison for different processing methods used to produce biochar from biomass. Different technologies, as discussed in Section 2, do influence functional properties of end products derived from various thermochemical treatments. Pyrolysis, gasification, torrefaction and HTC are the thermochemical treatments used to produce solid products together with other solid constituents from biomass. However, pyrolysis is the most acceptable processing method to convert biomass into biochar since it matches IBI guidelines. Solid products produced from both gasification and torrefaction are not regarded as biochar since the end product of these processes does not match the properties of biochar. However, hydrochar, a group of biochar, matches with the functional properties of biochar, especially from slow pyrolysis.

Table 4 shows possible comparison among chars derived from various biomass via different thermal treatments in terms of operating condition and product yield. Conventional low efficiency pyrolysis can result in loss of roughly around 80–90% of biomass weight (wet basis) and the majority of the original biomass's energy content (McHenry 2009). Hence, it is important to make suitable system-configuration for eliminating such loss to a level that is insignificant. Generally, the lower temperature, at which pyrolysis occurs, can yield higher carbon recovery of original biomass (Lehmann *et al.* 2006) and lower ash

Table 4 | Comparison of biochar derived from various biomass via different thermal conversion technologies

Feedstock	Process	Temperature (°C)	Heating rate (°C/min)	Time	Ash (%)	Fixed carbon (%)	Solid yield (%)	Reference
Fruit cuttings	Slow pyrolysis	600	10	1 h	4.6	21.1	37.5	Agirre *et al.* (2013)
		600	10	2 h	9.3	76.5	37.0	
		600	10	3 h	10.9	73.9	38.0	
		750	10	1 h	15.6	76.6	32.5	
		750	10	2 h	11.15	79.4	31.0	
		900	10	2 h	17.59	79.9	29.0	
Switchgrass	Slow pyrolysis	300	5	2.5 min	6.7	20.5	70.9	Pilon & Lavoie (2011)
		300	5	5 min	5.3	24.7	65.6	
		400	5	2.5 min	11.8	53.9	27.3	
		400	5	5 min	14.6	52.2	25.3	
		500	5	2.5 min	26.6	52.6	12.4	
		500	5	5 min	23.8	54.6	12.3	
Safflowers seeds	Slow pyrolysis	400	10	30 min	7.5	67.3	34	Angın (2013)
		400	30	30 min	8.5	70.2	30	
		400	50	30 min	8.5	71.7	28.5	
		450	10	30 min	8.2	71.8	31	
		450	30	30 min	8.5	72.8	29	
		450	50	30 min	8.6	74	28	
		500	10	30 min	8.5	74	29	
		500	50	30 min	8.7	77.0	26.6	
Spruce	HTC	175	12	30 min	0.11	14.7	88	Bach *et al.* (2013)
		200	12	30 min	0.12	15.92	80	
		225	12	30 min	0.14	25.12	70	
Coconut fiber	HTC	220	5	30 min	6.2	24	76.6	Liu *et al.* (2013)
		250	5	30 min	5	27.1	65.7	
		300	5	30 min	4.3	42.1	65	
		350	5	30 min	4.9	38.5	55.7	

yield. When compared to raw biomass feedstock, the hydrochar samples, produced by the HTC process, had a significant reduction in ash content, whereas slow-pyrolysis biochar, when compared to raw biomass, had a higher proportion of ash. Dry feedstock has given higher biochar yield. The heat generated can adequately warm the entering feedstock to initiate pyrolysis reactions, allowing the process to continue. Furthermore, char formation is favoured when temperatures and oxygen levels inside the pyrolyzing chamber are low (Banik *et al.* 2018).

Pyrolysis at high pressure increases biochar output by converting pyrolytic vapors to secondary biochar (Tomczyk *et al.* 2020). However, production of biochar at higher temperature condition and pressure incur higher production costs. Hence, low-temperature pyrolysis may be suitable for small land holders and entrepreneurs dealing with biochar production. The ideal temperature for biochar formation in terms of carbon recovery, CEC, and surface area is 500 °C (Tomczyk *et al.* 2020). High temperature and low heating rates with long gas residence time maximize gas-fuel yield. Biochar production is optimized at low temperature and low heating rates set inside the pyrolyzing chamber (Banik *et al.* 2018).

The chemical composition, aromaticity, and pore structure of biochar were significantly affected by particle size, heating rate, and residence time (Xie *et al.* 2015). In fast pyrolysis, the shorter vapor residence time is important for the secondary reactions. In slow pyrolysis, the vapor is confined and reacted extensively with the solid phase. Hence, more mass ends up as char. The percentage of carbon can be increased by increasing pyrolysis temperature and time together with reduction in percentage oxygen and surface hydrophobicity (Yu *et al.* 2009). Temperature increase led to a decrease in char production. The significant drop in yield between 400 and 500 °C was brought on by the partial gasification of lignin and hemicellulose. Furthermore, progressive aromatization occurred at higher pyrolysis temperatures with an increase in its surface area.

Char yield, percentage hydrogen and percentage oxygen dropped in materials set with longer pyrolysis period (Burhenne & Aicher 2014). Table 5 describes the surface area and pore volume of biochar produced at different pyrolysis temperatures. Generally, surface area increases as pyrolysis temperature increases. However, at 700 °C, a reduction in surface area has been seen. At higher pyrolysis temperatures, the aliphatic, alkyl, and ester groups may be destroyed, and the aromatic lignin core is exposed, thereby increasing the surface area. A significant relationship between micropore volume and surface area indicates that pore size distribution plays a significant role in the expansion of biochar's surface area. Biochar made from animal waste and solid waste feedstock have lower surface areas than biochar made from agricultural waste and wood biomass, even at higher pyrolysis temperatures. It has been reported that biochar samples made between 500 and 700 °C had been well carbonized with high surface area (>300 m^2/g), little organic matter ($<3\%$) and low oxygen content ($<10\%$). Additionally, chars produced between 300 and 400 °C were partly carbonized and had the surface area of 200 m^2/g; 40–50% organic carbon; and more than 20% oxygen (Chun *et al.* 2004).

In contrast to low-temperature chars, which reacted through surface adsorption and some concurrent partitioning into the residual organic matter, high temperature chars were active through adsorption onto their carbonized surfaces. At 600 °C, the most surface area was produced, and as the pyrolysis temperature increased, the overall acidity reduced (Sun *et al.* 2014). Due to stronger carbonization of cellulose and hemicellulose at 700 °C, a higher char output was produced at 400 °C. Due to pore blockage by organic compounds with a high ash content, surface area, and pore size reduced for temperature values between 400 and 700 °C. Pyrolysis temperature is the key factor which determines biochar yield significantly. A study conducted on the conversion of cotton seed hulls into biochar at pyrolyzing temperature ranging from 200 to 800 °C. It showed that a rapid decrease in biochar yield had been recorded at the temperature greater than 400 °C due to the loss of volatile matter and gas, whereas at temperature less than 400 °C, a steady biochar yield was observed (Tran *et al.* 2016).

Another research was conducted to determine how pyrolysis temperature (200–400 °C) affected the production of the biochar. This study involved in a systematic comparison of several biochar made from grass and wood biomass. A rapid decrease in biochar yield was reported at temperature lesser than 300 °C due to initial dehydration reactions. Additionally, it has been demonstrated by X-ray diffraction (XRD) analysis that biochar made from grass and wood exhibited turbostratic crystallites at temperatures higher than 400 °C. In addition, a significant deviation in aromatic carbon was evidenced by X-ray diffraction (Keiluweit *et al.* 2010). However, it has been reported that, when the pyrolysis temperature rises, the plant-based biomass dehydrates and depolymerizes into smaller dissolved products of lignin and cellulose (Keiluweit *et al.* 2010). The pyrolysis temperature affects the morphology and structural changes of biochar. In general, surface area increases as pyrolysis temperature rises. However, it has also been noted that the surface area decreases at temperatures higher than 700 °C (Chatterjee *et al.* 2020).

An increase in surface area results from the destruction of aliphatic, alkyl and ester groups and the exposure of the aromatic lignin core at higher pyrolysis temperatures (Lewis & Fletcher 2013). In general, at temperatures greater than 500 °C, biochar

Table 5 | Surface area and pore volume of biochar produced at different pyrolysis temperature

Feedstock	Pyrolysis temperature (°C)	Yield (%)	Surface area (m²/g)	Pore volume (cm³/g)	Reference
Buffalo weed	300	50.0	1.4	0.005	Yakkala et al. (2013)
Buffalo weed	700	29.0	280	0.157	
Fescue straw	300	75.8	4.5	–	Keiluweit et al. (2010)
Fescue straw	500	31.4	50.0	–	–
Fescue straw	700	28.8	139.0	–	–
Orange peel	150	82.4	22.8	0.023	Chen & Chen (2009)
Orange peel	300	37.2	32.3	0.031	
Orange peel	600	26.7	7.8	0.008	
Peanut shell	300	36.9	3.1	–	Ahmad et al. (2012a)
Peanut shell	700	21.9	448.2	0.200	
Pine shaving	200	95.9	2.3	–	Keiluweit et al. (2010)
Pine shaving	400	35.3	28.7	–	
Pine shaving	700	22.0	347.0	–	
Poplar wood	400	32.0	3.0	–	Kloss et al. (2012)
Poplar wood	460	–	8.2	–	
Poplar wood	525	–	35.7	–	
Poultry manure	300	65.7	4.3	0.012	
Poultry manure	600	47.0	3.7	0.019	
Poultry manure	700	47.0	6.6	0.02	
Rapeseed plant	400	39.4	16.0	1.244	Karaosmanoğlu et al. (2000)
Rapeseed plant	600	32.2	17.6	1.263	
Rapeseed plant	800	28.2	19.0	1.155	
Swine solid	350	62.3	3.54	0.9	Cantrell et al. (2012)
Swine solid	620	49.0	–	–	
Tire rubber	200	93.5	–	–	Lian et al. (2011)
Tire rubber	600	54.5	51.5	0.120	
Tire rubber	800	43.0	50.0	0.110	
Wheat straw	400	34.0	4.8	–	Kloss et al. (2012)
Wheat straw	460	–	2.8	–	
Wheat straw	525	–	14.2	–	

surface becomes less polar. Biochar produced at 400 °C was with high polarity and more effective for remediation purpose (Ahmad et al. 2014). Biomass undergoes series of reactions in the conversion process into biochar. Understanding the mechanisms of such reactions in various thermal treatments would help to select an appropriate production method to produce biochar from biomass materials. However, these mechanisms are very complicated and partially understood. Hence, proper comparison of various thermal treatments in terms of biochar yield and functional groups is highly essential for future works.

This part of the overview tends to compare and summarize two major processes: HTC and slow pyrolysis, used commonly to produce solid materials such as hydrochar and biochar for environmental remediation. The polymeric component of biomass degrades and depolymerizes during thermochemical conversion, producing solid, liquid, and gaseous by-products. The temperature profile maintained in the reaction chamber determines the process scenario. The highest reaction temperature is the key factor that controls the reaction mechanism and character of biochar yielded. There are some chemical reactions such as decarboxylation, dehydration, decarbonylation, de-methoxylation, intermolecular derangement, aromatization and condensation commonly occurred during the thermochemical conversion process of biomass materials (Kambo & Dutta 2014).

Reaction mechanism and temperature significantly influence the thermal stability of the structural compounds of biomass. The decomposition of hemicellulose takes place between 200 and 300 °C. It is followed by cellulose that decomposes between 300 and 400 °C. However, lignin is decomposed at 600 °C since it is stable to heat (Yang *et al.* 2004). However, in HTC, decomposition of hemicellulose and cellulose starts between 160 and 180 °C in the of lignin (Kumar *et al.* 2020). The degradation of such compounds in HTC is controlled by similar mechanisms available in pyrolysis. However, the presence of hot compressed water causes hydrolysis, which causes the breakage of ether and ester bonds between monomeric sugars. This process starts the destruction of biomass, and the addition of one water molecule enables the process to begin (Kambo & Dutta 2014). HTC yields char with high lignin contents as of the wash off of hemicellulose and cellulose by hydrolysis. The degradation of hemicellulose during HTC results in the formation of 2,5-hydroxyl-methyl-furfural (HMF) (Kambo & Dutta 2015). Its concentration increases with increasing temperature. Additionally, the hydrochar particles created by the HTC process frequently have a slightly porous surface with increased adsorption capability (Jang *et al.* 2018). The formation of 2,5-HMF in the aqueous phase is dependent on the operational conditions, temperature, and other parameters (Kambo & Dutta 2015; Kumar *et al.* 2020).

2.6. Comparison of biochar and hydrochar

Production of both biochar and hydrochar is an emerging sector in the field of environmental engineering. As discussed above, there are various methods used to produce solid matter from the biomass. However, each process is defined by its own boundary. Gasification and torrefaction have been eliminated from the discussion as they yield solid materials that do not match the typical properties of biochar. Hence, two processes, pyrolysis and HTC, are considered suitable for producing char from biomass residues. Anyhow, the validation of these two processes require significant scientific work. This part, therefore, tends to deeply discuss the properties of biochar and hydrochar based on literature. HTC and pyrolysis have distinct reaction phases in the total reaction cycle. Therefore, the end product characteristics vary significantly from one another.

The presence of undesirable alkali and alkaline metallic compounds in biomass is a huge challenge for their application in energy sector. These compounds may lead to undesirable behaviors like slagging, fouling and corrosion during combustion (Kambo & Dutta 2014). The percentage of these compounds is directly related to percentage of ash. Hence, if either biochar or hydrochar is used for power generation, their ash content has to be reduced. HTC reduces the ash content by demoralizing these organic constituents in the liquid product stream since the HTC process is carried out in the hot water. In contrast to raw biomass, the ash content of biochar samples, produced during pyrolysis, showed an upward trend. The processing temperature and the hemicellulose to lignin ratio have an impact on the amount of volatile solids and carbon yield in char samples.

High mass yield and low carbon conversion efficiency are produced by low-temperature processes, whereas the process completed at high temperatures is completely opposite. As HTC is carried out in hot water, the heated compressed water in the container heats up, partially transforming the hemicellulose and cellulose into an aqueous phase and causing a substantial mass loss of the solid yield. As the yield density rises with an increase in reaction time and temperature in both methods, the solid yield and H/C-O/C ratio decrease. According to the results of the Van-Krevelen analysis performed on the char samples, both chars had lower H/C-O/C ratio than the raw feedstock. The H/C-O/C ratio for the hydrochar samples, on the other hand, was reported to be greater and more similar to those of natural coal than for biochar produced by slow pyrolysis. This shows that, as compared to the slow pyrolysis process, HTC has a larger ratio of decarboxylation to dehydration reaction rates (Kambo & Dutta 2015).

The reaction temperature of the processing reactor of both chars do influence physiochemical properties of biochar prominently. At temperatures exceeding 160 °C, the polymeric component of biomass goes through a sequence of chemically aided reactions that form char with conditioned surface structures (Pavlovič *et al.* 2013). The surface structural configuration and functional properties of both chars are significantly different from each other, though improved aromatic features, surface area and porosity are seen in both processes. Turbo-strategically arranged graphite links are formed in chars produced via slow pyrolysis and the spacing between these layers increase with an increase in the reaction temperature (Lehmann & Joseph 2015). Amyl carbon compounds dominate biochar samples produced at around 350 °C with little proportions of alkyl-O and alkyl-C.

As the temperature goes further to above 500 °C, these alkyl O and alkyl C are completely converted to aryl-C that leads to low H/C ratio (Kambo & Dutta 2015). Furthermore, well organized and spherical shape carbonaceous nanoparticles are generally formed at the surface of the hydrochar obtained from HTC as of its reduced thermal reaction in the presence of compressed hot water. A study conducted with biochar prepared with swine manure at 650 °C via pyrolysis with 2 h residence

time. The char samples from pyrolysis contained aromatic groups on its surface, whereas the hydrochar samples from the HTC were dominated by alkyl moieties (Akdeniz 2019). Hence, it has been concluded that the process temperature is a crucial factor which determines functional properties of biochar and hydrochar produced via pyrolysis and HTC, respectively.

Furthermore, physical constituents and physiochemical properties of both chars are also influenced by reaction pathways of both chars. Free radical process is the reaction pathway of slow pyrolysis, whereas HTC reaction pathway is set with strong hydrolysis due to the presence hot water in the reaction phase. In pyrolysis, free radical pathway is induced by homolytic cleavage of bonds, which takes place at 300 °C (Shafizadeh 1982). The tar compounds produced by the breakdown and degradation of cellulose are mainly made of anhydrosugars, which are less reactive than the free radicals created during bond breakage when temperature is raised to about 500 °C. The inorganic chemicals and tar vapors in the biomass feedstock volatilize and later condense in the porous structure of the biochar, which is responsible for the cross-linked crystal layer structure (Wornat et al. 1995; Kambo & Dutta 2015).

However, in the HTC process, the presence of hot compressed water causes the first reaction phase to be initiated by the hydrolysis of biological macromolecules, resulting in the formation of oligosaccharides, including xylose, glucose, and fructose. This is followed by a dehydration reaction, in which hexose and pentose are transformed into furfural compounds. These substances, then, go through a number of further processes such as dehydration, condensation and polymerization. Spherically shaped carbonaceous nanoparticles with size distributions ranging from 0.5 to 5 m are produced as a result (Tomczyk et al. 2020). Many operating parameters are controlling the end product quality of both chars. However, since degradation, melting of biomass, release of volatiles, synthesis of intermediate compounds, and their further forms are all temperature dependent, temperature, among other factors, is the most essential element, governing the total reaction process.

High heating rate (HHR) is also another factor that controls heat and mass transfer along with the rate of the formation intermediates. Furthermore, the mass yield of char is significantly reduced when produced under thermochemical process at very high high retention time (HRT) and HHR. For example, char yield of less than 10–30% can be obtained from gasification and pyrolysis at high temperature. The char yield is, therefore, highly reduced as temperature goes up. It has been reported that, during pyrolysis of safflower seeds with reaction temperature in the range of 400–600 °C, the surface area of the biochar reduced with an increase in heating rates (Angın 2013). Moreover, very high reaction temperature and heating rates can destroy the fine porous structure and cause devolatilization of volatile organic matter in the pore structure of the biochar, resulting in the clogging of pores and reduction in the overall surface area (Kloss et al. 2012; Kambo & Dutta 2015).

Additionally, rapid heating can cause the porous structure of char's alkali and alkaline earth metallic compositions to melt. As a result, it might have a negative effect on surface area and porosity. In contrast, the surface area of char produced via HTC is poor together with deformed porous space. Results of an experiment revealed that the surface area of biochar and hydrochar obtained via pyrolysis at 550 °C for 15 min and HTC at 250 °C for 4 h of corn stover were 12 and 4 m^2/g, respectively (Fuertes et al. 2010). Another study, with pine wood, reported a surface area of 21 m^2/g for samples obtained from HTC at 300 °C for 20 min with the heating rate of 10 °C/min, and the surface area of 29 m^2/g was obtained for the same feedstock processed using pyrolysis at 700 °C for 2 h at the heating rate of 10 °C/min (Liu et al. 2010). It has been reported that, with an increase in reaction temperature from 150 to 250 °C, the surface area of hydrochar produced from palm empty fruit bunches increased from 6.08 to 8.03 m^2/g. However, with the further increase in temperature to 350 °C, the surface area of the hydrochar reduced to 2.04 m^2/g. Furthermore, scanning electron macroscopic images of hydrochar samples showed the loss of fibrous structures with an increase in reaction temperature, resulting in the formation of a smooth surface. This evidence can be taken to explain the reason behind the reduction in the surface area with an increase in reaction temperature (Parshetti et al. 2013). It is, therefore, important to select appropriate production technique to produce both biochar and hydrochar according to the need.

3. OUTLINE OF TECHNIQUES USED FOR BIOCHAR MODIFICATION FOR BETTER FUNCTIONALITIES

Biochar science is a growing field nowadays as of its significant importance in environmental remediation and management. As discussed above in Section 2, biochar is produced by different ways. However, its yield and functional properties are influenced by processing conditions and raw material characteristics. Therefore, processes, like pyrolysis, are to be activated by some modifications that enhance their functional properties important for reasonable remediation targets. Therefore, this part of the review tends to summarize the techniques used to modify biochar produced with some potential research evidence. There are many modification methods available to modify biochar for induced functional groups. These additional

modification steps are to increase surface area, porosity and functional groups of biochar samples produced via thermal pre-treatments. Modification by chemical agents, physical agents, treatments with mineral sorbents and magnetic modifications are commonly used to activate biochar for enhanced performance. Hence, a brief summary is made in Figure 3 for the better undestanding of diffferent modification methods and their effect on biochar properties. The properties such as pore volume, surface area and functional groups are increased by different modifications methods.

3.1. Modification by chemical agents

Various chemicals are used to treat biochar chemically to enhance their functional groups. This activation can be done in two ways: impregnation of raw biomass with the chemical argent and the thermal treatment after impregnation. This process will prevent the tar formation (El-Hendawy 2009). An activating chemical agent can be used for carbonization and activation at a temperature. In a two-step chemical activation process, raw feedstock is first carbonized, then the carbonized product is activated by mixing with a chemical agent or being pre-treated before the carbonization process (Sajjadi et al. 2019).

Chemical treatments of biochar after production by various chemical agents have induced the performance of the biochar as an amendment or sorbent (Ahmed et al. 2016). Chemical treatment usually involves with an addition of acid or base. Furthermore, intentional oxidation using hydrogen peroxide (H_2O_2), potassium permanganate ($KMnO_4$), ammonium persulphate [$(NH_4)_2S_2O_8$] and ozone (O_3) have also been used for surface modification of functional groups (Wang & Wang 2019). The use of strong acids like phosphoric acid (H_3PO_4), sulphuric acid (H_2SO_4), nitric acid (HNO_3) and hydrochloric acid (HCl) have also been investigated for the surface oxidation purposes that can improve surface acidity and porous structure of biochar (Rajapaksha et al. 2016). The use of H_3PO_4 is very common and reliable for chemical modification, and it is more efficient than other hazardous chemicals (Budinova et al. 2006). In order to prevent shrinkage or contraction during

Figure 3 | Types of modification of biochar.

the formation of porosity, the H_3PO_4 is used to decompose lignocellulosic, aliphatic, and aromatic components while creating phosphate and polyphosphate cross bridges (Zuo et al. 2009).

Furthermore, some mineral acids such as HNO_3, H_2SO_4 and HCl, have also been used for the modification of biochar. It has been reported that the use of HNO_3 as oxidizing agent caused micropore destruction due to its erosive nature, resulting in a decrease in total surface area (Ania et al. 2004). The reduction of biochar porosity from 10 to 40% has also been reported in biochar sample treated with concentrated H_2SO_4 (Guo & Lua 2000). Excess water vapor movement toward the surface of the biochar with concentrated H_2SO_4 could impart surface area development (Guo et al. 2005). A surface area increase of 250 fold has been observed in biochar samples treated with 30% H_2SO_4 and oxalic acid compared to unmodified biochar samples (Vithanage et al. 2015). Acidic functional groups on the carbonized surface, like amine and carboxylic groups, can be stimulated by the application of acidic chemicals, which will increase the surface's ability to bind metals and create new active sites. In order to effectively pyrolyze biochar, it is necessary to thoroughly investigate the effectiveness of different chemicals.

Some base materials are also used to modify biochar for better improvements. Potassium hydroxide activation (KOH) is a common application in biochar modification. This activation can be performed at room temperature or an elevated temperature. Potassium, from a precursor chemical, during this activation, separates the lamellae of crystallites that form the carbon structure. Rinsing the sample with potassium is necessary to have improved surface area and porosity (Joseph & Lehmann 2009). It has been reported that a two-stage KOH activation process of pre-carbonized precursors has produced larger surface area in biochar samples together with additional surface hydroxyl groups (El-Hendawy 2009). The use of NaOH in the chemical modification of biochar is economical compared to KOH. However, such modification at lower temperature is inefficient for the development of very poor surface area and micropores (Lillo-Ródenas et al. 2003). Therefore, further studies are required to understand the science behind this action.

The creation of additional sorption surfaces increases surface area; increase the electrostatic attraction; promote functional groups; and increase surface groups of chemically modified biochar, which is important for better sorption affinities. A scientific investigation revealed that H_2O_2 treatment of biochar had increased the amount of carboxyl groups on biochar surface and provided additional cation exchange site for surface complexion of Pb^{2+}, Zn^{2+}, Cu^{2+} and Cd^{2+} (Wang & Liu 2018). It has been reported that modified biochar by KOH significantly improved its sorption capacity to As^{5+} due to increased surface area, pore volume and alteration of functional groups on the surface (Jin et al. 2014). Surface area and pore volume of different modified biochar are listed in Table 6. Overall, surface area and pore volume of all the biochar increase with modification and pyrolysis temperature.

3.2. Surface modification for functional groups

Chemical modification is done sometimes for the surface functional groups to suit for particular environmental remediation process (Islam et al. 2015). Acidic functional groups such as carboxylic, lactonic and phenolic groups can be modified using chemical oxidation with HNO_3, $KMnO_4$ and H_3PO_4 at relatively low temperature (Li et al. 2014b). An increase in carboxylic content from 2.1 to 8.2% has been reported in an experiment conducted by H_2O_2 modification (Tan et al. 2011). Single stage modification is commonly used for carboxyl group modification. Furthermore, treatments with acids like H_3PO_4 or H_2SO_4 also partially oxidize carbon surface and enrich carboxylic groups on the surface (Qian et al. 2015; Rajapaksha et al. 2016). The science behind this process is still unknown. It needs to be studied using scientific concepts.

Base metal cations, like Cu, Zn and Cd, can be attracted by N-containing functional groups in environmental remediation applications. These N-containing functional groups can be attained by nitration followed by reduction in carbon surface (Wan & Li 2018). Nitronium ions are formed as HNO_3 dissociation occurs in biochar modification with HNO_3, which then react with aromatic rings of biochar-nitrate products on the active surface of biochar (Yang & Jiang 2014). The nitration process occurs via electrophilic aromatic substitution that introduces nitrogen groups onto aromatic rings in biochar (Godwin et al. 2019). This surface amination usually stimulates the introduction of amino-groups that are responsible for the strong affinity to pollutants. Amine functional groups on the biochar surfaces can be conducted by chitosan modification that promotes the adsorptive capacity of chars to heavy metal pollutants such as Pb^{2+}, Cu^{2+} and Cd^{2+} (Zhou et al. 2013). This modification draws vast attention in the heavy metal remediation process.

The amine groups of chitosan enable high metal uptake due to the formation of strong chemical bonds with metal ions (Zhou et al. 2013). Furthermore, application of H_2O_2 as a modifying agent of peanut hull biochar has increased functional groups, like carboxylic groups, that enhanced heavy metal adsorption (Xue et al. 2012). In addition, KOH modification also improved O-containing functional groups and improved tetracycline sorption capacity (Liu et al. 2012). Some organic

Table 6 | Modification and characterization of different biochar

Modification	Raw material	Temperature (°C)	Surface area (m²/g)	Pore volume (cm³/g)	Reference
Magnetic biochar	Paper mill sludge	700 – Unmodified	67.0	0.083	Devi & Saroha (2014)
		700 – Modified	101.2	0.079	
Magnetic biochar	Orange peel	400 – Unmodified	28.1	0.041	Chen et al. (2011)
		400 – Modified	23.4	0.042	
Metal-impregnated activated carbon	Pulverized coal	600 and 1,000 – Unmodified	190.0	0.079	Dastgheib et al. (2014)
		600 – Unmodified	245.0	0.126	
		600 – Modified	463.1	0.022	
Clay biochar composites	Bagasse	600 – Unmodified	388.3	–	Yao et al. (2014)
		600 – Modified	407.0	–	
Steam-activated biochar	Tea waste	300 – Unmodified	2.3	0.006	Rajapaksha et al. (2014)
		300 – Modified	1.5	0.004	
Steam-activated biochar	Tea waste	700 – Unmodified	342.2	0.22	Rajapaksha et al. (2014)
		700 – Modified	576.1	0.109	
H_2O_2 modification	Peanut	300 – Unmodified	96.9	–	Xue et al. (2012)
		300 – Modified	114.4	–	
KOH modification	Rice husk	450 to 500 – Unmodified	34.4	0.028	Liu et al. (2012)
		450 to 500 – Modified	117.8	0.073	
Methyl modification	Rice husk	450 – Unmodified	51.9	0.031	Jing et al. (2014)
		450 – Modified	66.0	0.051	

solvents are also used to modify biochar for their better functional groups, especially carboxylic group. However, the use of acidic methanol for modification is expensive, though it improves surface functional groups (Jing et al. 2014). Electron donor–acceptor formation between the surface of biochar and organic pollutants were promoted by the biochar with high ester content and hydroxyl groups modified by methanol (Jing et al. 2014).

Surfactants are widely used to modify the surface properties of different solid materials such as zeolite and bentonite, in recent years. In addition to this, it is used as an additive in industrial production. They are grouped into different categories: cationic group, anionic group and non-ionic group and gemini surfactant, according to their hydrophilic groups (Paria 2008). Cationic surfactants can easily be captured by biochar surface of negative charge via electrostatic attraction and exchange with exchangeable cations such as Mg^{2+}, Na^+ and K^+ (Erdinç et al. 2010). It has been reported that non-ionic exchange played a major role in the cationic surfactant cetylpyridinium chloride's sorption on granular charcoal at low concentration levels (Saleh 2006). Non-ionic surfactant can also be attracted by charcoal via physisorption at low free energy levels of sorption (Dey 2012). However, both monomolecular and micellar-anionic surfactants are not easily attracted due to electrostatic repulsion on the surface of the biochar (Fujita et al. 1991).

Increased concentrations of cetyltrimethyl ammonium bromide decreased biochar sorption capacity (Han et al. 2013). Certain selected metal oxides are used to improve the surface properties of biochar, which enhance sorption capacity of chars. For example, biochar coated with metal oxides can show promising potential if it is used to adsorb anionic dyes. Sorption capacity of biochar to anionic dyes is weak as of the electrostatic repulsion between negatively charged biochar surface and dye molecule (Rajapaksha et al. 2016). In addition, due to the production of iron oxides on the biochar surface, the performance of the iron oxide-coated biochar was greatly improved when compared to unmodified biochar

(Tchomgui-Kamga et al. 2010). Furthermore, coating of biochar with Fe^{3+} greatly increased As^{3+} and As^{5+} sorption capacities (Samsuri et al. 2013). The scientific concepts of these processes are still limited and need further expansion.

It has been identified that the sorption capacity of MgO coated biochar for anions was significantly higher than the uncoated biochar by about five times because of the improvement in the surface properties with active functional groups (Zhang et al. 2012). An experimental study revealed that the coating of biochar with cobalt had significantly increased the sorption of Cr^{6+} (Wang et al. 2012). Furthermore, biochar coated with carbon nanotubes that are very efficient for pollutant removal because of their high surface area and nanostructure. However, its high cost makes this application very limited. Hybrid multi-walled carbon nanotube coated biochar exhibited higher surface area, porosity and thermal stability compared to uncoated biochar (Miao et al. 2010). Table 7 describes the sorption capacity of different biochar modified by different chemical agents. Generally, biochar surface properties, especially surface area and porosity, are enhanced by chemical modification. Therefore, the adsorptive performance is also increased.

Biochar is coated with graphene that has two dimensional structure and unique properties, mechanical strength, surface area, thermal conductivity and electrical conductivity (Fang et al. 2020). Its application has also been limited because of complex separation procedures for reuse and recovery. Increased sorption of phenol and methylene blue by graphene coated biochar has been reported in an experiment (Li et al. 2020). This increased sorption is due to increased surface area and pore volume after such coating. Physical activation is also done to increase the adsorptive capacity of biochar to contaminants in environmental remediation processes.

In physical activation, high porous structure is formed by the cavitation process with CO_2 as CO_2-C interaction removes the C atoms from the solid material by burning, resulting such closed porous structure. Physical modification methods are simple and economically feasible. Furthermore, this process uses no chemicals except some oxidizing agents, like carbon dioxide, steam and air. Activated biochar with enhanced carbonaceous structures and high surface area is developed by steam activation of conventional biochar. Steam activation may alter the characteristics of biochar by releasing the confined products of incomplete combustion during thermal treatment (Manyà 2012).

Moreover, steam activation process is known to create new porosities and enlarged diameters of smaller pores created during pyrolysis (Lima et al. 2010). It has been reported that conventional biochar's inorganic and organic sorption capacities were increased when it was activated by an oxidizing agent like steam. An experimental investigation revealed that biochar made from invasive plant species and steam activated tea waste had a potential ability to remove veterinary medicines from water (Vithanage et al. 2015). Modification of biochar with high temperature CO_2 ammonia mixture treatment has been investigated to adsorb gases. Introduction of N-containing groups onto the biochar can increase N content up to 3.91% (wet basis) due to ammonification.

It has been reported that biochar modified using CO_2 showed improved surface area and pore volume compared to unmodified biochar (Xiong et al. 2013). Impregnation with mineral oxidize is an emerging concept to improve the functional properties of biochar. Usually clay minerals have the potential to remove contaminants because of their composition, surface charge, cation exchange capacity and mineralogical structure. Montmorillonite, gibbsite and kaolinite are among the most commonly used clay minerals as low-cost sorbents (Rajapaksha et al. 2016). Pre-soaking of pine wood biomass in $MnCl_2.4H_2O$ solution and subsequent pyrolysis yielded MnO-modified biochar (Wang et al. 2015b). The $KMnO_4$ addition to biochar significantly changed the surface area and pore volume of biochar (Zheng et al. 2021). There is a need to understand the scientific mechanism behind the impregnation needs to be explained.

Table 7 | Comparison of adsorption capacity of biochar modified via chemical argents

Method of modification	Sorbate	Sorption capacity	Enhancement	Reference
H_2SO_4 + Oxalic acid	Sulfamethazine	155.1 mg/kg	Increased porosity	Vithanage et al. (2015)
H_2SO_4 KOH	Tetracycline	23.26 mg/g and 58.82 mg/g	Increased porosity, C and O contentment	Liu et al. (2012)
KOH	Cu^{2+} and Cd^{2+}	31 mg/g and 34 mg/g	Increased sorption by 20 times	Regmi et al. (2012)
KOH	As^{5+}	30.98 mg/g	Increased sorption	Jin et al. (2014)
H_2O_2	Hg	1,470.5–1,347.9 μg/g	Increased sorption	Tan et al. (2011)
H_2O_2 oxidation	Pb^{2+}	28.82 mg/g	Increased sorption by 20 times	Inyang et al. (2012)

The benefits of MnO_x and biochar have been combined in an attempt to produce new, modified biochar composites with improved functional properties. It has been reported that the Mg-biochar nanocomposites, produced from Mg-enriched plant tissues, showed an effective adsorption for P in aqueous phase (Yao et al. 2013). Magnetic modification is done to biochar to facilitate their separation after preparation. Sorption capacity of biochar for anionic ions is low because of its negative charge on the surface. Therefore, magnetic modification is used to promote the sorption capacity of biochar to anionic ions (Tan et al. 2020). A magnetic biochar was created by chemically precipitating Fe^{3+} and Fe^{2+} onto orange peel powder, followed by pyrolyzing the mixture at various temperatures to create iron oxide magnetic formation. This magnetic biochar's hybrid sorption property facilitates the remove phosphate and organic contaminants efficiently (Chen et al. 2011). The overall summary of biochar modification is summarized in Table 8.

4. POTENTIAL APPLICATIONS OF BIOCHAR IN ENVIRONMENTAL REMEDIATION PROCESS

Biochar has wide range of potential applications in environmental remediation and sustainability because of its multifunctional capacity. Biochar has been produced by number of distinct processing methods. However, each processing method produces biochar with specific properties that are affected by many factors as described in Section 2. Furthermore, various modification methods are being practiced to improve the capacity of biochar for better future applications as discussed in Section 3 of this overview. This part, hence, summarizes the potential applications of biochar in the environmental remediation process with some prominent research highlights in order to give an overview for those who involve in biochar science that is becoming popular nowadays as of its promising functionalities. Figure 4 outlines the possible applications of biochar with respective functional features.

4.1. Biochar for energy production

Biochar is used effectively for long-term storage of carbon molecules that play a crucial role in the climate change and in greenhouse gas emission. The application of biochar into soil is a popular strategy for the CO_2 mitigation in the environment (Qambrani et al. 2017). However, the stability of biochar in the soil is influenced by number of factors, out of which production method is most significant to consider (Ameloot et al. 2013).

The production method, such as slow pyrolysis, releases many harmful gases into environment. Therefore, controlling this gas emission is complex and expensive. Moreover, self-heating of biochar may lead to burning of stockpiles. It is also difficult to produce biochar from wet feedstock (Arriola et al. 2020). However, the HTC process can convert biomass of various feedstock into hydrochar without requiring any pre-heating arrangements, yielding low emissions of harmful gases into environment compared to slow pyrolysis (Di Blasi et al. 1999). At the presence of highly concentrated surface oxygen groups in hydrochar, autoignition of piles has been restricted. Anyhow, the use of hydrochar to sequester carbon is still questionable because of its less stability to microbial decomposition. Furthermore, in-depth research work is needed to promote its potential applications in soil for the long-term storage of carbon (Kambo & Dutta 2015).

4.2. Biochar for improving agricultural productivity

Application of biochar to soil helps in improved population of soil beneficial organisms together with an increased soil aeration, resulting in the improvement of crop yield because of the development of structured rhizosphere (Hussain et al. 2018). Freshly produced biochar is hydrophobic in nature with very low amount of functional groups on its surface. However, it becomes hydrophilic with large functional groups as it is exposed to soil due to the oxidation by soil oxygen. These functional groups can exchange cation exchange capacity, nutrient retention capacity and water holding capacity that are important for better crop yield (Bolan et al. 2022). Moreover, very little information on the application of chars produced via HTC to the soil improvement is available. It has been reported that the negative effect of adding hydrochar into soil on crop yield had been observed in an experiment conducted with Lolium perenne. Anyhow, great attention has to be given when applying biochar/hydrochar to the soil in the presence of heavy metals because these applications may interrupt the existing food chains. Hence, further research is needed to investigate the real effect of biochar or hydrochar applied on soil properties and microbial dynamics in order to validate its use as a soil amendment for better crop yield.

### 4.3. Biochar for the sorption of contaminants in the environmental remediation process

Carbonaceous materials have been used to remove contaminants present in the various sources of environment. Activated carbon with increased surface area and porosity is a commonly used carbonaceous sorbent for environmental pollutants.

Table 8 | Summary of biochar modification methods, contaminant removal, and production temperature

Modification method	Biochar feedstock	Temperature (°C)	Target group	Enhancement	Reference
Chemical modification ($KMnO_4$/HNO_3/NaOH)	Bamboo	550	Furfural	Inhibited sorption of furfural	Li et al. (2014b)
H_2O_2 modification	Peanut hull	300	Pb^{2+}, Cu^{2+}, Ni^{2+} and Cd^{2+}	Increased Pb^{2+} sorption from 0.88 to 22.82 mg/g and increased O-containing functional groups	Xue et al. (2012)
Chemical modification (10% H_2SO_4 and 3M KOH)	Rice husk	450–500	Tetracycline	Exhibited better sorption and larger surface area	Liu et al. (2012)
NaOH activation	Pine chip	300	Diclofenac Naproxen	Increased sorption	Jung et al. (2015)
HCl activation and coating with iron	Wheat straw	450	NO^{3-} and PO_4^{3-}	Increased sorption	Li et al. (2016)
H_3PO_4 activation	Pine tree sawdust	550	Fluoride	Increased sorption and surface area	Guan et al. (2015)
Chemical modification ($Mg(OH)_2$)	Conocarpus	400	Fe^{2+}	Increased sorption	Usman et al. (2013)
Modification by ethanol	Rice husk	400–500	Tetracycline	45.6% sorption increased in 12 h and increased O-containing groups	Liu et al. (2012)
Amino modification	Saw dust	500	Cu^{2+}	Enhanced sorption	Yang & Jiang (2014)
Steam activation	Maize stover	350	Emission of N_2O and CH_4	Reduced CH_4 and N_2O emissions	Fang et al. (2014)
Steam activation	Tea waste	300 and 700	Sulfamethazine	Increased sorption and surface area	Rajapaksha et al. (2014)
Integration with mineral sorbents	Corn straw	600	Cd^{2+}	Increased sorption	Song et al. (2014)
Clay biochar composites	Bamboo and bagasse	600	Methylene blue	Increased sorption	Yao et al. (2014)
Chitosan-modified biochar	Bamboo and sugarcane bagasse	600	Cu^{2+} and Cd^{2+}	Increased removal	Yong et al. (2013)
Mineral addition (Kaolin and Calcite)	Rice straw	200, 300, 400 and 500	C retention	Increased C retention and C stability	Li et al. (2014a)
Manganese oxide modification	Pine wood	600	As^{3+} and Pb^{2+}	Increased sorption by 4.7 and 20.1 times, respectively	Wang et al. (2015a)
Fe impregnated biochar	Hickory chips	600	Arsenic	Increased sorption upto 2.16 mg/g	Hu et al. (2015)
Magnetic modification	Orange peel	250, 400 and 700	Phosphate	–	Chen et al. (2011)

Biochar, therefore, does match with the functional properties of activated carbon because of the structured thermal pre-treatments in the production process (Guo & Lua 2000). The presence of O-containing carbonyl, hydroxyl and phenolic functional groups could be useful to remove environmental contaminants. The multifunctional effects of biochar show its potential as an effective environmental sorbent to contaminants present in soil and water. As properties of biochar are influenced by number of processing conditions, critical selection must be made to produce biochar with enhanced functional groups.
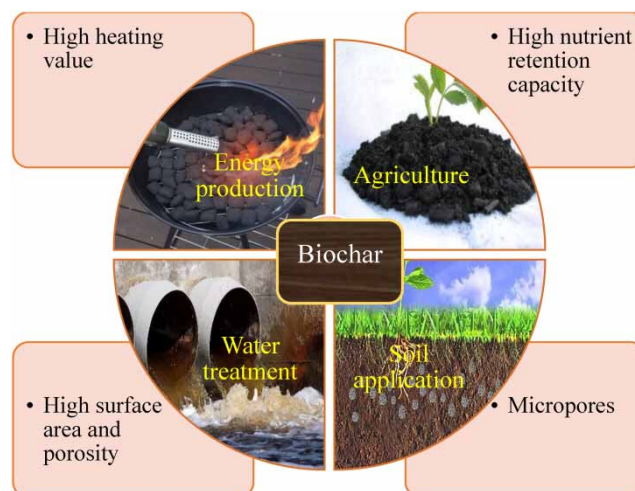
Figure 4 | Applications of biochar in environmental remediation.

4.3.1. Water treatment

The characteristics of biochar similar to activated carbon have attracted researchers for contaminant removal from water (Cheng *et al.* 2021). Its applications have been classified into organics (dyes, phenolics, polynuclear aromatics and antibiotics) and inorganics (cations and anions) remediation. The disposal of industrial dyes into water bodies causes severe environmental problems. Many textile dyes are difficult to destroy by conventional waste treatment methods since such compounds resist decomposition by light, oxidizing agents and aerobic digestion. A study dealt with the development of biochar with bamboo biomass to remove dyes from water and wastewater (Mui *et al.* 2010). Furthermore, pyrolysis rice husk biochar was applied to Malachite Green (MG) adsorption (Leng *et al.* 2015). Rice straw biochar was made in a vertical tubular reactor for 2 h from 200 to 700 °C under nitrogen. About 95% of MG was removed within 40 min from the solution with 25 mg/L of initial MG concentration (Hameed & El-Khaiary 2008).

Biochar at pH 6.5 adsorbed more Rhodamine B (RB) than commercially activated carbon at pH 3 because the dye molecules are more easily accessed by the larger micropores of biochar than fine pores of activated carbon (Mohan *et al.* 2014). Biochar from canola straw, peanut straw, soybean straw and rice hulls were used to remove Methyl Violet (MV) from water (Xu *et al.* 2011). Moreover, bamboo char was used to remove Acid Blue 25 (AB 25), Acid Yellow 117 (AY 117), Methyl Blue (MB) and Acid Black 172 (AB 172) effectively (Lyu *et al.* 2016). Hornbeam sawdust biochar was used to adsorb Orange 30, and the optimum adsorption occurred at pH 2. The adsorption capacity was highest on the char made at 800 °C (Ates & Tezcan Un 2013). Another potential adsorption process involves in the electrostatic attraction/repulsion of biochar and organic pollutants. Solution chemistry, such as pH and ionic strength, may also affect the sorption of organics onto biochar.

The sorption capacity of biochar, derived from crop residue at 350 °C, for MV increased from pH 7.7 to 8.7 (Xu *et al.* 2011). Industries dealing with plastics, dyes and drugs, antioxidants and pesticides handle phenolic compounds for their manufacturing process. These are highly toxic as far as the food chain and food web are concerned. However, nitrophenols and chlorophenols are common pollutants that pollute drinking water. An experiment has been conducted to investigate the effect of the biochar prepared at fixed temperatures and different residence times from rice husk and corn cob on phenol adsorption. Biochar prepared using 1.6 s exhibited a higher phenol adsorption capacity (589 mg/L) (Mohan *et al.* 2014). Many pesticides such as organophosphates, organochlorins, carbamate, triazin and chlorophenoxy acid compounds are used in agriculture to improve crop yield.

However, these chemicals do cause severe problems to the environment. Hence, significant attention is drawn to the remediation of these chemicals by the application of biochar. Dibromochloropropane, a soil fumigant, used to control nematodes, was adsorbed from well water onto almond shell activated biochar (Klasson *et al.* 2013). Orange peel biochar from slow pyrolysis, ranging from 150 to 700 °C, was used for naphthalene and 1-napthol adsorption. Maximum adsorption capacities for 1-napththol and naphthalene were achieved by orange peel biochar obtained at 200 and 700 °C, respectively (Chen *et al.* 2011). In some studies, biochar has been used to remove benzene and nitrobenzene from water (Chun *et al.*

2004). Furthermore, trichloroethylene has been successfully removed from the water by chars, produced from soybean stover and peanut shells, pyrolyzed at 300 and 700 °C, respectively. Chars produced at 700 °C had higher surface area than those at 300 °C.

Heavy metals present in the drinking water pose serious health hazards as they go into the living tissues. These cause serious health threats even at very low concentrations. Some are capable of assimilation along the food chain. The organisms at higher levels of food chain will be affected physiologically. The discharge of heavy metals into water bodies is to be prohibited in order to avoid ill health conditions. Biochar has been successfully used to adsorb Cr, Cu, Pb, Cd, Hg, Fe, Zn and As ions. Biochar, a by-product of bio-oil production, can be used to remove heavy metal ions from water. This is the cost-effective method compared to activated carbons. Biochar, from slow pyrolysis and hydrothermal treating of rice husk, olive pomace, orange waste and compost, was used for Cu^{2+} remediation (Mohan *et al.* 2014). Slow pyrolysis char at 600 °C was less efficient for Cu^{2+} removal than those produced at 300 °C, but slow pyrolysis chars removed more Cu^{2+} than hydrothermal chars. Table 9 describes the potential application of biochar for the remediation of organic and inorganic pollutants. Herbicides, antibiotics, pesticides, polycyclic aromatic hydrocarbons and dyes are among the most well-known organic pollutants. Partitioning, sorption of organic pollutants and electrostatic interactions between organic contaminants and biochar play a major role in the remediation applications, whereas mobilization, complexation, precipitation and reduction are the mechanisms involved between inorganic contaminant and biochar.

Heavy metals were removed from water using biochar generated from pig and cow dung at 400 and 600 °C under ambient pressure and nitrogen, followed by chemical and mechanical treatment. The highest surface area was found in the chemically treated pig manure char at 600 °C for the removal of Cu^{2+}, Zn^{2+}, Cd^{2+}, and Pb^{2+} from water (Kołodyńska *et al.* 2012). In addition, switch grass biochar was almost created using HTC at 300 °C in a high pressure reactor. KOH was used to activate this biochar, increasing porosity and unclogging some of its partly blocked pores. These chars removed Cu^{2+} and Cd^{2+} from aqueous solutions effectively (Regmi *et al.* 2012). Buffalo weed chars were prepared via slow pyrolysis for Cd^{2+} and Pb^{2+} removal (Yakkala *et al.* 2013).

Sugarcane pulp residue biochar via slow pyrolysis at 500 °C gave maximum Cr^{3+} uptake at pH 5.1 (Yang *et al.* 2013). Some biochar is used to remove anions for water. Slow pyrolysis chars prepared from orange peels and water treatment sludge of 400, 600 and 700 °C were also used for fluoride uptake (Oh *et al.* 2012). Orange peel biochar made at 400 and 700 °C adsorbed more fluoride than chars from water treatment sludge made at 400 °C. Bench scale slow pyrolysis of anaerobically digested sugar beet tailings gave good removal efficiency for PO_4^{3-} ions from aqueous solution (Yao *et al.* 2011). Biochar research in anionic removal from water is limited because biochar surfaces have negatively charged particles that repulse anions falling off the surfaces. However, more energy has to be invested to increase the sportive capacity of biochar over anions by modifying their surfaces.

4.4. Soil applications

Compared to water remediation, there are limited researches available on applying biochar to soils polluted with organic contaminants. In an experimental investigation, the long-term impact of biochar on simazine-contaminated soil was evaluated (Ahmed *et al.* 2016). Atrazine sorption to the organic carbon content of biochar produced from dairy manure at 450 °C shows that larger dissolved organic carbon contents in soil may inhibit atrazine sorption by clogging the pores of the biochar (Cao & Harris 2010). This is because of the high surface area and micro porosity of biochar. Therefore, the pyrolysis conditions with which the biochar is formed should be well defined. Before being used for the remediation of certain organic pollutants in soil, the characteristics of biochar should be thoroughly improved.

Most of the inorganic contaminants originate from a range of anthropogenic sources such asmining, melting, metal finishing, fertilizers, wastewater and sewage sludge. Inorganic pollutants, especially heavy metals, do resist decomposition. Biochar has recently been applied as a novel carbonaceous material to absorb metals in soil. Biochar has distinct effect on mobility of metals in soils. Application of hard wood derived biochar to multi-element (Pb, Cu, Cd and Zn) contaminated soil mobilized Cu, while Cd and Zn were immobilized in soils amended (Lu *et al.* 2014). Furthermore, another research study reported Cu mobility in soil due to increased dissolved organic carbon with the addition of chicken manure derived biochar (Zhang *et al.* 2013).

The electrostatic repulsion between anionic Sb and negatively charged biochar surface could have resulted in desorption of Sb. Conversely, the electrostatic attraction between positively charged Cu and negatively charged biochar surface is the prevailing mechanism of Cu immobilization in soil (Uchimiya *et al.* 2011b). However, the biochar, produced at high temperature (>600 °C), is generally deficient in dissolved organic carbon, which could affect Cu immobility in soil (Tomczyk *et al.* 2019).

Table 9 | Application of biochar for pollutant removal

Biochar type	Contaminant	Effect	Reference
Dairy manure (450 °C)	Atrazine	Sorption	Cao *et al.* (2011)
Woodchips (450 and 850 °C)	Carbofuran	Adsorption due to higher surface area	Yu *et al.* (2009)
Bamboo (600 °C)	Pentachlorophenol	Reduced leaching due to diffusion	Xu *et al.* (2012)
Hard wood (450 and 600 °C)	Simazine	Sorption due to micropores	Jones *et al.* (2011)
Pine wood (350 and 700 °C)	Phenanthrene	Entrapment in micro and mesopores	Zhang *et al.* (2010)
Sewage (500 °C)	Poly aromatic hydrocarbons	Partitioning	Khan *et al.* (2013)
Hard wood (400 °C)	Arsenic	Mobilization due to enhanced pH	Hartley *et al.* (2009)
Hard wood	Arsenic and copper	Mobilization due to enhanced pH	Beesley *et al.* (2010)
Chicken manure (550 °C)	Cadmium, copper and lead	Immobilization due to portioning of metals from exchangeable phase	Park *et al.* (2011)
Oak wood	Copper and lead	Complexion with phosphorous and organic matter	Uchimiya *et al.* (2012)
Dairy manure (450 °C)	Lead	Immobilization	Cao *et al.* (2009)
Oak wood (400 °C	Lead	Immobilization	Ahmad *et al.* (2012b)
Rice straw	Lead	Non-electrostatic adsorption	Nadarajah *et al.* (2021)
Cottonseed hulls (200–800 °C)	Nickel, copper, lead and cadmium	Controlled metal sequestration of surface functional groups	Uchimiya *et al.* (2011a)
Dairy manure (200 °C)	Atrazine	Sorption	Cao & Harris (2010)
Cotton straw (450 and 850 °C)	Chloropyrifos	Adsorption	Yu *et al.* (2009)
Red gum wood chips (450 and 850 °C)	Pyrimethanil	Adsorption	Yu *et al.* (2010)
Grass and wood (200 and 600 °C)	Norflurazon	Sorption	Sun *et al.* (2011)
Rice husk (450–500 °C)	Tetracycline	Interaction	Liu *et al.* (2012)
Rice and wheat straw	Brilliant blue	Electrostatic attraction	Qiu *et al.* (2009)
Crop residue (350 °C)	Methyl violet	Electrostatic attraction	Xu *et al.* (2011)
Orange peel (150–700 °C)	Naphthalene	Adsorption	Chen & Chen (2009)
Corn stover (600 °C)	Pyrene	Adsorption	Hale *et al.* (2012)
Oak wood (400–450 °C)	Chromium	Sorption	Mohan *et al.* (2011)
Pecan shell (800 °C)	Copper	Sorption on humic acid	Ippolito *et al.* (2012)
Soybean straw (500 °C)	Copper, cadmium and zinc	Adsorption	Lima *et al.* (2010)
Sewage sludge (550 °C)	Lead	Adsorption	Khan *et al.* (2013)
Soybean stalk (300–700 °C)	Mercury	Precipitation and reduction	Kong *et al.* (2011)

Moreover, pyrolysis temperature of biochar production has a strong effect on the mobility of heavy metals in the soil. The biochar produced at low temperature is favourable for immobilizing Pb (Igalavithana *et al.* 2017). In addition, soil pH is considered to greatly influence mobility of metals. Biochar shows the potential to mitigate Cr contaminated soils as they are highly reactive with many functional groups, and are able to donor electrons (Choppala *et al.* 2012).

The effect of biochar on remediation of soil contaminated with organic and inorganic contaminants has received little attention. Many factors influence the mechanisms of such remediation. Functional properties of biochar are strongly affected by pyrolysis temperature that impacts on the sorption efficiencies for both organic and inorganic contaminants. Chars produced at higher temperature have greater surface area and developed pore structures, whereas biomass pyrolyzed at low temperatures is efficient for inorganic contaminants due to the presence of O-containing functional groups and greater release of cations. In addition, many factors such as type of contaminant, type of biochar, production condition and functional properties of biochar do influence sorption capacities. Hence, care must be taken before applying biochar to remediate

contaminated soil at a larger scale. More importantly, research on biochar is contemporary and still needs in-depth investigation to determine long-term effects of biochar applied to contaminated areas.

5. CONCLUSIONS

Biochar applications in environmental remediation have the potential to control and manage environmental pollutants that come out of various industrial processes and chemical sources. The research in this area is developing at a faster rate because of positive research outcomes from biochar experiments conducted to solve various environmental problems. However, the quality of biochar and their sorptive capacities are influenced by processing methods. Therefore, the produced biochar has to be modified by different means to enhance their functional properties for better adsorption of environmental pollutants, and it has to be suitable for vast environmental remediation processes. This article hence tends to give an overview of various biochar processing methods, modification methods and environmental applications of biochar based on some structured literature under an umbrella.

The following are the major inferences that have been drawn from this review article: biochar could be produced by the commonly used methods such as pyrolysis, gasification, dry torrefaction and HTC. Pyrolysis is the thermal decomposition of biomass in the temperature range of 350–600 °C. It is categorized to be either fast or slow based on its residence time. Slow pyrolysis produces high char yield (35% wet basis) compared to fast pyrolysis (10% wet basis). Dry torrefaction is set in the temperature range of 200–300 °C, and it is just the beginning of the pyrolysis. Hence, the end product from this cannot be considered as char. Moreover, gasification is the partial burning of biomass in the temperature range 600–1,200 °C with the major yield of syngas mixture. However, HTC draws great attention in the char science because it yields high percentage of solid matter with enhanced surface properties.

HTC is performed in the temperature range of 180–260 °C at an elevated pressure of 2–5 MPa for 5–240 min. The end product of this process is called hydrochar, which is comparable to biochar from slow pyrolysis. This article, hence, has given some considerations for the comparison of hydrochar and biochar. Many research works have been done in the slow pyrolysis and summarized that the process of char production is critically controlled by reaction temperature compared to other factors. Hence, great attention has to be given to the control of temperature in the conversion of biomass by thermal treatments. However, HTC of biomass residuals for the production of hydrochar is still in its early stage of development, and therefore there are many aspects that require additional research. Moreover, based on the literature summary made in this paper, it is clearly explained that the hydrochar from HTC has improved physiochemical properties that are useful for various environmental applications.

However, being a process with high conversion efficiency when compared to other pre-treatments, its applicability at an industrial scale is not favourable. Hence, further investigations are needed to make the HTC process simple for commercial application with declined reaction pressure. Moisture content of feedstock used to produce chars has the great influence on char recovery from pyrolysis process. The main advantage of the HTC process is the elimination of pre-drying requirement of a feedstock. Therefore, non-conventional biomasses, like animal waste, food wastes, green vegetable waste and other higher moisture content feedstock, should be prioritized because of their utilization and economical inapplicability to conventional dry-thermal pre-treatments. Biochar modification is done for improving functional properties of biochar in order to improve the sorptive capacities.

Based on the literature summarized in this paper, modification of chars by various means changes its surface properties, functional groups, pore volume and distribution. Among the modification methods discussed, chemical activation process is an appealing strategy to improve the sorption capacity of biochar for both organic and inorganic contaminants. However, special attention needs to be given to the modification process so as to minimize the effect of modification on the stability of biochar in order to avoid environmental contamination. Furthermore, magnetic modification has to be promoted for better separation and recovery problems of non-magnetic sorbents. Biochar has various applications in the field of environmental remediation. Based on this overview, it has the potential to remediate soil and water contaminated with number of organic and inorganic contaminants.

However, a particular type of biochar may not be applicable for many contaminants since the removal process is influenced by the number of variables. The complex nature of soil systems, compared to aquatic systems, has limited biochar applications to soil. Pyrolysis condition and feedstock type are two major factors that determine sorptive capacity of biochar. However, it is obvious that the use of biochar, as an environmental sorbent, can have strong implications. Converting waste biomass into biochar will also promise an effective solution for the safe and beneficial disposal of number of waste materials. In particular,

materials such as animal litter and sewage sludge that have pathogens will be sterilized through thermal conversion. Furthermore, applying biochar to remediate contaminated soil will additionally provide means of carbon sequestration leading to climate change mitigation.

6. DIRECTIONS TO FUTURE WORKS

Biochar science is popular in the environmental remediation process nowadays. Hence, in-depth scientific investigations must be carried out for making its application viable for a wide range of environmental problems. Therefore, this part of the overview suggests some areas for researchers to look into the research gaps identified for better knowledge dissemination. Biochar is now being produced by various feedstock under different production conditions. Therefore, comparison of their efficiencies is very difficult. Furthermore, studies of biochar preparation by several methods from the same feedstock, followed by the adsorption of same adsorbents, are rare. Hence, it is needed to produce particular biochar from the same feedstock, followed by adsorption studies of the same adsorbents that are needed to access the reproducibility.

Biochar, produced from feedstock via either slow pyrolysis or fast pyrolysis, has varying contents of percentage oxygen and percentage carbon. Moreover, some chars will be useful for a small number of uses, while some may have wide range of use. Each of these should be studied in detail to compare the results. The information on HTC is very limited. The HTC process is influenced not only by temperature but also by elemental properties of feedstock and processing conditions such as reaction pressure, residence time, solid-loading ratio and particle size distribution. These are also important parameters for designing industrial HTC plants to produce hydrochar at a larger scale. However, limited information is available on such parameters that influence HTC. Hence, incorporation of this valuable information by structured scientific work is highly required to establish an appropriate HTC processing protocol to produce hydrochar with enhanced characteristics.

Moreover, HTC process optimization is needed under unique production conditions to optimize properties of hydrochar for better environmental applications. Functions of biochar in dynamic soil systems are influenced by complex variables. Limited studies have been focused on this investigation. Each variable that influences the functions of biochar in any systems should be studied scientifically. Moreover, long-term field experiments on biochar applications to contaminated soils are needed in order to understand its long-term functions in soil. Many methods are used to modify the surface functional properties of biochar to enhance their sportive capacities. However, the information, presented in this review is from laboratory experiments. A very limited scientific information is available on large scale production of engineered biochar. Hence, an attempt is needed to scale up existing biochar modification methods and to test its performance in the field.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Agirre, I., Griessacher, T., Rösler, G. & Antrekowitsch, J. 2013 Production of charcoal as an alternative reducing agent from agricultural residues using a semi-continuous semi-pilot scale pyrolysis screw reactor. *Fuel Process. Technol.* **106**, 114–121.

Ahmad, M., Lee, S. S., Dou, X., Mohan, D., Sung, J. K., Yang, J. E. & Ok, Y. S. 2012a Effects of pyrolysis temperature on soybean stover- and peanut shell-derived biochar properties and TCE adsorption in water. *Bioresour. Technol.* **118**, 536–544.

Ahmad, M., Soo Lee, S., Yang, J. E., Ro, H. M., Han Lee, Y. & Sik Ok, Y. 2012b Effects of soil dilution and amendments (mussel shell, cow bone, and biochar) on Pb availability and phytotoxicity in military shooting range soil. *Ecotoxicol. Environ. Saf.* **79**, 225–231.

Ahmad, M., Upamali, A., Eun, J., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Soo, S. & Sik, Y. 2014 Chemosphere Biochar as a sorbent for contaminant management in soil and water : A review. *Chemosphere* **99**, 19–33.

Ahmed, M. B., Zhou, J. L., Ngo, H. H., Guo, W. & Chen, M. 2016 Progress in the preparation and application of modified biochar for improved contaminant removal from water and wastewater. *Bioresour. Technol.* **214**, 836–851.

Akdeniz, N. 2019 A systematic review of biochar use in animal waste composting. *Waste Manage.* **88**, 291–300.

Ameloot, N., Graber, E. R., Verheijen, F. G. A. & De Neve, S. 2013 Interactions between biochar stability and soil organisms: Review and research needs. *Eur. J. Soil Sci.* **64**, 379–390.

Angın, D. 2013 Effect of pyrolysis temperature and heating rate on biochar obtained from pyrolysis of safflower seed press cake. *Bioresour. Technol.* **128**, 593–597.

Ania, C. O., Parra, J. B. & Pis, J. J. 2004 Oxygen-induced decrease in the equilibrium adsorptive capacities of activated carbons. *Adsorpt. Sci. Technol.* **22**, 337–352.

Antal, M. J. & Grønli, M. 2003 The art, science, and technology of charcoal production. *Ind. Eng. Chem. Res.* **42**, 1619–1640.

Arriola, E., Chen, W. H., Chih, Y. K., De Luna, M. D. & Show, P. L. 2020 Impact of post-torrefaction process on biochar formation from wood pellets and self-heating phenomena for production safety. *Energy* **207**, 118324.

Ates, F. & Tezcan Un, U. 2013 Production of char from hornbeam sawdust and its performance evaluation in the dye removal. *J. Anal. Appl. Pyrolysis* **103**, 159–166.

Bach, Q. V., Tran, K. Q., Khalil, R. A., Skreiberg, Ø. & Seisenbaeva, G. 2013 Comparative assessment of wet torrefaction. *Energy and Fuels* **27**, 6743–6753.

Banik, C., Lawrinenko, M., Bakshi, S. & Laird, D. A. 2018 Impact of pyrolysis temperature and feedstock on surface charge and functional group chemistry of biochars. *J. Environ. Qual.* **47**, 452–461.

Beesley, L., Moreno-Jiménez, E. & Gomez-Eyles, J. L. 2010 Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil. *Environ. Pollut.* **158**, 2282–2287.

Bergman, P. C. a., Boersma, a. R., Zwart, R. W. R. & Kiel, J. H. a. 2005 Torrefaction for biomass co-firing in existing coal-fired power stations. *Energy Res. Cent.* 58–59. Netherlands ECN ECNC05013.

Bolan, N., Hoang, S. A., Beiyuan, J., Gupta, S., Hou, D., Karakoti, A., Joseph, S., Jung, S., Kim, K. H., Kirkham, M. B., Kua, H. W., Kumar, M., Kwon, E. E., Ok, Y. S., Perera, V., Rinklebe, J., Shaheen, S. M., Sarkar, B., Sarmah, A. K., Singh, B. P., Singh, G., Tsang, D. C. W., Vikrant, K., Vithanage, M., Vinu, A., Wang, H., Wijesekara, H., Yan, Y., Younis, S. A. & Van Zwieten, L. 2022 Multifunctional applications of biochar beyond carbon storage. *Int. Mater. Rev.* **67**, 150–200.

Brick, S., Lehmann, J. & Kramer, J. 2010 Biochar : Assessing the Promise and Risks To Guide US. Policy Author.

Brownsort, P. A. 2009 Biomass pyrolysis processes: review of scope, control and variability. United Kingdom Biochar Res. Centre, London 1, UK, 1–39.

Budinova, T., Ekinci, E., Yardim, F., Grimm, A., Björnbom, E., Minkova, V. & Goranova, M. 2006 Characterization and application of activated carbon produced by H_3PO_4 and water vapor activation. *Fuel Process. Technol.* **87**, 899–905.

Burhenne, L. & Aicher, T. 2014 Benzene removal over a fixed bed of wood char: The effect of pyrolysis temperature and activation with CO_2 on the char reactivity. *Fuel Process. Technol.* **127**, 140–148.

Cantrell, K. B., Hunt, P. G., Uchimiya, M., Novak, J. M. & Ro, K. S. 2012 Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. *Bioresour. Technol.* **107**, 419–428.

Cao, X. & Harris, W. 2010 Properties of dairy-manure-derived biochar pertinent to its potential use in remediation. *Bioresour. Technol.* **101**, 5222–5228.

Cao, X., Ma, L., Gao, B. & Harris, W. 2009 Dairy-manure derived biochar effectively sorbs lead and atrazine. *Environ. Sci. Technol.* **43**, 3285–3291.

Cao, X., Ma, L., Liang, Y., Gao, B. & Harris, W. 2011 Simultaneous immobilization of lead and atrazine in contaminated soils using dairy-manure biochar. *Environ. Sci. Technol.* **45**, 4884–4889.

Chatterjee, R., Sajjadi, B., Chen, W. Y., Mattern, D. L., Hammer, N., Raman, V. & Dorris, A. 2020 Effect of pyrolysis temperature on physicoChemical properties and acoustic-based amination of biochar for efficient CO2 adsorption. *Front. Energy Res.* **8**, 1–18.

Chen, B. & Chen, Z. 2009 Sorption of naphthalene and 1-naphthol by biochars of orange peels with different pyrolytic temperatures. *Chemosphere* **76**, 127–133.

Chen, B., Chen, Z. & Lv, S. 2011 A novel magnetic biochar efficiently sorbs organic pollutants and phosphate. *Bioresour. Technol.* **102**, 716–723.

Cheng, N., Wang, B., Wu, P., Lee, X., Xing, Y., Chen, M. & Gao, B. 2021 Adsorption of emerging contaminants from water and wastewater by modified biochar: A review. *Environ. Pollut.* **273**, 116448.

Choppala, G. K., Bolan, N. S., Megharaj, M., Chen, Z. & Naidu, R. 2012 The influence of biochar and black carbon on reduction and bioavailability of chromate in soils. *J. Environ. Qual.* **41**, 1175–1184.

Chun, Y., Sheng, G., Chiou, G. T. & Xing, B. 2004 Compositions and sorptive properties of crop residue-derived chars. *Environ. Sci. Technol.* **38**, 4649–4655.

Dastgheib, S. A., Ren, J., Rostam-Abadi, M. & Chang, R. 2014 Preparation of functionalized and metal-impregnated activated carbon by a single-step activation method. *Appl. Surf. Sci.* **290**, 92–101.

Demirbaş, A. 2001 Biomass resource facilities and biomass conversion processing for fuels and chemicals. *Energy Convers. Manage.* **42**, 1357–1378.

Devi, P. & Saroha, A. K. 2014 Synthesis of the magnetic biochar composites for use as an adsorbent for the removal of pentachlorophenol from the effluent. *Bioresour. Technol.* **169**, 525–531.

Dey, S. 2012 Enhancement in hydrophobicity of low rank coal by surfactants – A critical overview. *Fuel Process. Technol.* **94**, 151–158.

Di Blasi, C., Signorelli, G., Di Russo, C. & Rea, G. 1999 Product distribution from pyrolysis of wood and agricultural residues. *Ind. Eng. Chem. Res.* **38**, 2216–2224.

El-Hendawy, A. N. A. 2009 An insight into the KOH activation mechanism through the production of microporous activated carbon for the removal of Pb 2 + cations. *Appl. Surf. Sci.* **255**, 3723–3730.

Erdinç, N., Göktürk, S. & Tunçay, M. 2010 A study on the adsorption characteristics of an amphiphilic phenothiazine drug on activated charcoal in the presence of surfactants. *Colloids Surf., B* **75**, 194–203.

Fang, C., Zhang, T., Li, P., Jiang, R. F. & Wang, Y. C. 2014 Application of magnesium modified corn biochar for phosphorus removal and recovery from swine wastewater. *Int. J. Environ. Res. Public Health* **11**, 9217–9237.

Fang, Z., Gao, Y., Bolan, N., Shaheen, S. M., Xu, S., Wu, X., Xu, X., Hu, H., Lin, J., Zhang, F., Li, J., Rinklebe, J. & Wang, H. 2020 Conversion of biological solid waste to graphene-containing biochar for water remediation: A critical review. *Chem. Eng. J.* **390**, 124611.

Fuertes, A. B., Arbestain, M. C., Sevilla, M., Fiol, S., Smernik, R. J., Aitkenhead, W. P., Arce, F. & Macias, F. 2010 Chemical and structural properties of carbonaceous products obtained by pyrolysis and hydrothermal carbonisation of corn stover. *Aust. J. Soil Res.* **48**, 618–626.

Fujita, I., Tomooka, J. & Sugimura, T. 1991 Sorption of anionic surfactants with wood charcoal. *Bull. Chem. Soc. Jpn.* **64**, 738–740.

Gao, N., Kamran, K., Quan, C. & Williams, P. T. 2020 Thermochemical conversion of sewage sludge: A critical review. *Prog. Energy Combust. Sci.* **79**, 100843.

Godwin, P. M., Pan, Y., Xiao, H. & Afzal, M. T. 2019 Progress in preparation and application of modified biochar for improving heavy metal ion removal from wastewater. *J. Bioresour. Bioprod.* **4**, 31–42.

Guan, X., Zhou, J., Ma, N., Chen, X., Gao, J. & Zhang, R. 2015 Studies on modified conditions of biochar and the mechanism for fluoride removal. *Desalin. Water Treat.* **55**, 440–447.

Guan, G., Kaewpanha, M., Hao, X. & Abudula, A. 2016 Catalytic steam reforming of biomass tar: Prospects and challenges. *Renew. Sustain. Energy Rev.* **58**, 450–461.

Guo, J. & Lua, A. C. 2000 Textural characterization of activated carbons prepared from oil-palm stones pre-treated with various impregnating agents. *J. Porous Mater.* **7**, 491–497.

Guo, J., Xu, W. S., Chen, Y. L. & Lua, A. C. 2005 Adsorption of NH_3 onto activated carbon prepared from palm shells impregnated with H_2SO_4. *J. Colloid Interface Sci.* **281**, 285–290.

Hale, S. E., Hanley, K., Lehmann, J., Zimmerman, A. R. & Cornelissen, G. 2012 Erratum: Effects of chemical, biological, and physical aging as well as soil addition on the sorption (Environmental Science and Technology (2011) 45 (10445-10453) of pyrene to activated carbon and biochar. *Environ. Sci. Technol.* **46**, 2479–2480.

Hameed, B. H. & El-Khaiary, M. I. 2008 Kinetics and equilibrium studies of malachite green adsorption on rice straw-derived char. *J. Hazard. Mater.* **153**, 701–708.

Han, D., Liu, X., Zhang, G., Sun, K. & Jiao, Y. 2013 Effects of cationic surfactant on pentachlorophenol sorption by sediment, active carbon and biochar. *Fresenius Environ. Bull.* **22**, 1280–1286.

Hartley, W., Dickinson, N. M., Riby, P. & Lepp, N. W. 2009 Arsenic mobility in brownfield soils amended with green waste compost or biochar and planted with Miscanthus. *Environ. Pollut.* **157**, 2654–2662.

He, C., Giannis, A. & Wang, J.-Y. 2013 Conversion of sewage sludge to clean solid fuel using hydrothermal carbonization: Hydrochar fuel characteristics and combustion behavior. *Appl. Energy* **111**, 257–266.

Hu, X., Ding, Z., Zimmerman, A. R., Wang, S. & Gao, B. 2015 Batch and column sorption of arsenic onto iron-impregnated biochar synthesized through hydrolysis. *Water Res.* **68**, 206–216.

Hussain, F., Hussain, I., Khan, A. H. A., Muhammad, Y. S., Iqbal, M., Soja, G., Reichenauer, T. G., Zeshan & Yousaf, S. 2018 Combined application of biochar, compost, and bacterial consortia with Italian ryegrass enhanced phytoremediation of petroleum hydrocarbon contaminated soil. *Environ. Exp. Bot.* **153**, 80–88.

Igalavithana, A. D., Lee, S. E., Lee, Y. H., Tsang, D. C. W., Rinklebe, J., Kwon, E. E. & Ok, Y. S. 2017 Heavy metal immobilization and microbial community abundance by vegetable waste and pine cone biochar of agricultural soils. *Chemosphere* **174**, 593–603.

Inyang, M., Gao, B., Yao, Y., Xue, Y., Zimmerman, A. R., Pullammanappallil, P. & Cao, X. 2012 Removal of heavy metals from aqueous solution by biochars derived from anaerobically digested biomass. *Bioresour. Technol.* **110**, 50–56.

Ippolito, J. A., Strawn, D. G., Scheckel, K. G., Novak, J. M., Ahmedna, M. & Niandou, M. A. S. 2012 Macroscopic and molecular investigations of copper sorption by a steam-activated biochar. *J. Environ. Qual.* **41**, 1150–1156.

Islam, M. A., Benhouria, A., Asif, M. & Hameed, B. H. 2015 Methylene blue adsorption on factory-rejected tea activated carbon prepared by conjunction of hydrothermal carbonization and sodium hydroxide activation processes. *J. Taiwan Inst. Chem. Eng.* **52**, 57–64.

Jang, H. M., Yoo, S., Choi, Y. K., Park, S. & Kan, E. 2018 Adsorption isotherm, kinetic modeling and mechanism of tetracycline on Pinus taeda-derived activated biochar. *Bioresour. Technol.* **259**, 24–31.

Jin, H., Capareda, S., Chang, Z., Gao, J., Xu, Y. & Zhang, J. 2014 Biochar pyrolytically produced from municipal solid wastes for aqueous As(V) removal: Adsorption property and its improvement with KOH activation. *Bioresour. Technol.* **169**, 622–629.

Jing, X. R., Wang, Y. Y., Liu, W. J., Wang, Y. K. & Jiang, H. 2014 Enhanced adsorption performance of tetracycline in aqueous solutions by methanol-modified biochar. *Chem. Eng. J.* **248**, 168–174.

Jones, D. L., Edwards-Jones, G. & Murphy, D. V. 2011 Biochar mediated alterations in herbicide breakdown and leaching in soil. *Soil Biol. Biochem.* **43**, 804–813.

Joseph, S. & Lehmann, J. 2009 *Biochar for Environmental Management: Science and Technology*. Earthscan, London, UK.

Jung, C., Boateng, L. K., Flora, J. R. V., Oh, J., Braswell, M. C., Son, A. & Yoon, Y. 2015 Competitive adsorption of selected non-steroidal anti-inflammatory drugs on activated biochars: Experimental and molecular modeling study. *Chem. Eng. J.* **264**, 1–9.

Kambo, H. S. & Dutta, A. 2014 Strength, storage, and combustion characteristics of densified lignocellulosic biomass produced via torrefaction and hydrothermal carbonization. *Appl. Energy* **135**, 182–191.

Kambo, H. S. & Dutta, A. 2015 A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications. *Renewable Sustainable Energy Rev.* **45**, 359–378.

Karaosmanoglu, F., Tetik, E. & Göllü, E. 1999 Biofuel production using slow pyrolysis of the straw and stalk of the rapeseed plant. *Fuel Process. Technol.* **59**, 1–12.

Karaosmanoğlu, F., Işıgigür-Ergüdenler, A. & Sever, A. 2000 Biochar from the straw-stalk of rapeseed plant. *Energy and Fuels* **14**, 336–339.

Kazemi Shariat Panahi, H., Dehhaghi, M., Ok, Y. S., Nizami, A. S., Khoshnevisan, B., Mussatto, S. I., Aghbashlo, M., Tabatabaei, M. & Lam, S. S. 2020 A comprehensive review of engineered biochar: Production, characteristics, and environmental applications. *J. Cleaner Prod.* **270**, 122462.

Keiluweit, M., Nico, P. S., Johnson, M. & Kleber, M. 2010 Dynamic molecular structure of plant biomass-derived black carbon (biochar). *Environ. Sci. Technol.* **44**, 1247–1253.

Khan, S., Wang, N., Reid, B. J., Freddo, A. & Cai, C. 2013 Reduced bioaccumulation of PAHs by Lactuca satuva L. grown in contaminated soil amended with sewage sludge and sewage sludge derived biochar. *Environ. Pollut.* **175**, 64–68.

Klasson, K. T., Ledbetter, C. A., Uchimiya, M. & Lima, I. M. 2013 Activated biochar removes 100% dibromochloropropane from field well water. *Environ. Chem. Lett.* **11**, 271–275.

Kloss, S., Zehetner, F., Dellantonio, A., Hamid, R., Ottner, F., Liedtke, V., Schwanninger, M., Gerzabek, M. H. & Soja, G. 2012 Characterization of slow pyrolysis biochars: effects of feedstocks and pyrolysis temperature on biochar properties. *J. Environ. Qual.* **41**, 990–1000.

Kołodyńska, D., Wnetrzak, R., Leahy, J. J., Hayes, M. H. B., Kwapiński, W. & Hubicki, Z. 2012 Kinetic and adsorptive characterization of biochar in metal ions removal. *Chem. Eng. J.* **197**, 295–305.

Kong, H., He, J., Gao, Y., Wu, H. & Zhu, X. 2011 Cosorption of phenanthrene and mercury(II) from aqueous solution by soybean stalk-based biochar. *J. Agric. Food Chem.* **59**, 12116–12123.

Kumar, A., Saini, K. & Bhaskar, T. 2020 Hydochar and biochar: Production, physicochemical properties and techno-economic analysis. *Bioresour. Technol.* **310**, 123442.

Lehmann, J. & Joseph, S. 2009 A future for biochar in Vermont. *Biochar Environ. Manag. Sci. Technol.* **416**.

Lehmann, J., Gaunt, J. & Rondon, M. 2006 Bio-char sequestration in terrestrial ecosystems – A review. *Mitig. Adapt. Strateg. Glob. Chang.* **11**, 403–427.

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C. & Crowley, D. 2011 Biochar effects on soil biota – A review. *Soil Biol. Biochem.* **43**, 1812–1836.

Leng, L., Yuan, X., Zeng, G., Shao, J., Chen, X., Wu, Z., Wang, H. & Peng, X. 2015 Surface characterization of rice husk bio-char produced by liquefaction and application for cationic dye (Malachite green) adsorption. *FUEL* **155**, 77–85.

Lewis, A. D. & Fletcher, T. H. 2013 Prediction of sawdust pyrolysis yields from a flat-flame burner using the CPD model. *Energy and Fuels* **27**, 942–953.

Li, F., Cao, X., Zhao, L., Wang, J. & Ding, Z. 2014a Effects of mineral additives on biochar formation: Carbon retention, stability, and properties. *Environ. Sci. Technol.* **48**, 11211–11217.

Li, Y., Shao, J., Wang, X., Deng, Y., Yang, H. & Chen, H. 2014b Characterization of modified biochars derived from bamboo pyrolysis and their utilization for target component (furfural) adsorption. *Energy and Fuels* **28**, 5119–5127.

Li, J. H., Lv, G. H., Bai, W. B., Liu, Q., Zhang, Y. C. & Song, J. Q. 2016 Modification and use of biochar from wheat straw (Triticum aestivum L.) for nitrate and phosphate removal from water. *Desalin. Water Treat.* **57**, 4681–4693.

Li, Z., Xing, B., Ding, Y., Li, Y. & Wang, S. 2020 A high-performance biochar produced from bamboo pyrolysis with in-situ nitrogen doping and activation for adsorption of phenol and methylene blue. *Chinese J. Chem. Eng.* **28**, 2872–2880.

Lian, F., Huang, F., Chen, W., Xing, B. & Zhu, L. 2011 Sorption of apolar and polar organic contaminants by waste tire rubber and its chars in single- and bi-solute systems. *Environ. Pollut.* **159**, 850–857.

Libra, J. A., Ro, K. S., Kammann, C., Funke, A., Berge, N. D., Neubauer, Y., Titirici, M. M., Fühner, C., Bens, O., Kern, J. & Emmerich, K. H. 2011 Hydrothermal carbonization of biomass residuals: A comparative review of the chemistry, processes and applications of wet and dry pyrolysis. *Biofuels* **2**, 71–106.

Lillo-Ródenas, M. A., Cazorla-Amorós, D. & Linares-Solano, A. 2003 Understanding chemical reactions between carbons and NaOH and KOH: An insight into the chemical activation mechanism. *Carbon N. Y.* **41**, 267–275.

Lima, I. M., Boateng, A. A. & Klasson, K. T. 2010 Physicochemical and adsorptive properties of fast-pyrolysis bio-chars and their steam activated counterparts. *J. Chem. Technol. Biotechnol.* **85**, 1515–1521.

Liu, Z., Zhang, F. S. & Wu, J. 2010 Characterization and application of chars produced from pinewood pyrolysis and hydrothermal treatment. *Fuel* **89**, 510–514.

Liu, P., Liu, W. J., Jiang, H., Chen, J. J., Li, W. W. & Yu, H. Q. 2012 Modification of bio-char derived from fast pyrolysis of biomass and its application in removal of tetracycline from aqueous solution. *Bioresour. Technol.* **121**, 235–240.

Liu, Z., Quek, A., Kent Hoekman, S. & Balasubramanian, R. 2013 Production of solid biochar fuel from waste biomass by hydrothermal carbonization. *Fuel* **103**, 943–949.

Liu, Y., He, Z. & Uchimiya, M. 2015 Comparison of biochar formation from various agricultural By-Products using FTIR spectroscopy. *Mod. Appl. Sci.* **9**, 246–253.

Lu, H., Zhang, W., Yang, Y., Huang, X., Wang, S. & Qiu, R. 2012 Relative distribution of Pb^{2+} sorption mechanisms by sludge-derived biochar. *Water Res.* **46**, 854–862.

Lu, K., Yang, X., Shen, J., Robinson, B., Huang, H., Liu, D., Bolan, N., Pei, J. & Wang, H. 2014 Effect of bamboo and rice straw biochars on the bioavailability of Cd, Cu, Pb and Zn to Sedum plumbizincicola. *Agric. Ecosyst. Environ.* **191**, 124–132.

Lynam, J. G., Coronella, C. J., Yan, W., Reza, M. T. & Vasquez, V. R. 2011 Acetic acid and lithium chloride effects on hydrothermal carbonization of lignocellulosic biomass. *Bioresour. Technol.* **102**, 6192–6199.

Lyu, H., Gong, Y., Gurav, R. & Tang, J. 2016 *Potential Application of Biochar for Bioremediation of Contaminated Systems, Biochar Application.* Elsevier Inc, Tianjin, China.

Mani, S., Sokhansanj, S., Bi, X. & Turhollow, A. 2006 Economics of producing fuel pellets from biomass. *E p f p b. Appl. Eng. Agric.* **22**, 421–426.

Manyà, J. J. 2012 Pyrolysis for biochar purposes: A review to establish current knowledge gaps and research needs. *Environ. Sci. Technol.* **46**, 7939–7954.

McHenry, M. P. 2009 Agricultural bio-char production, renewable energy generation and farm carbon sequestration in Western Australia: Certainty, uncertainty and risk. *Agric. Ecosyst. Environ.* **129**, 1–7.

McKendry, P. 2002 Energy production from biomass (part 1): Overview of biomass. *Bioresour. Technol.* **83**, 37–46.

Miao, H. Y., Chen, G. R., Chen, D. Y., Lue, J. T. & Yu, M. S. 2010 Hydrogen storage: A comparison of hydrogen uptake values in carbon nanotubes and modified charcoals. *EPJ Appl. Phys.* **52**, 21101.

Mohan, D., Pittman, C. U. & Steele, P. H. 2006 Pyrolysis of wood/biomass for bio-oil: A critical review. *Energy and Fuels* **20**, 848–889.

Mohan, D., Rajput, S., Singh, V. K., Steele, P. H. & Pittman, C. U. 2011 Modeling and evaluation of chromium remediation from water using low cost bio-char, a green adsorbent. *J. Hazard. Mater.* **188**, 319–333.

Mohan, D., Sarswat, A., Ok, Y. S. & Pittman, C. U. 2014 Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent – A critical review. *Bioresour. Technol.* **160**, 191–202.

Mojiri, A., Zhou, J. L., Robinson, B., Ohashi, A., Ozaki, N., Kindaichi, T., Farraji, H. & Vakili, M. 2020 Pesticides in aquatic environments and their removal by adsorption methods. *Chemosphere* **253**, 126646.

Mosier, N., Wyman, C., Dale, B., Elander, R., Lee, Y. Y., Holtzapple, M. & Ladisch, M. 2005 Features of promising technologies for pretreatment of lignocellulosic biomass. *Bioresour. Technol.* **96**, 673–686.

Mui, E. L. K., Cheung, W. H., Valix, M. & Mckay, G. 2010 Dye adsorption onto char from bamboo. *J. Hazard. Mater.* **177**, 1001–1005.

Mumme, J., Eckervogt, L., Pielert, J., Diakité, M., Rupp, F. & Kern, J. 2011 Hydrothermal carbonization of anaerobically digested maize silage. *Bioresour. Technol.* **102**, 9255–9260.

Nadarajah, K., Bandala, E. R., Zhang, Z., Mundree, S. & Goonetilleke, A. 2021 Removal of heavy metals from water using engineered hydrochar: Kinetics and mechanistic approach. *J. Water Process Eng.* **40**, 101929.

Oh, T. K., Choi, B., Shinogi, Y. & Chikushi, J. 2012 Effect of pH conditions on actual and apparent fluoride adsorption by biochar in aqueous phase. *Water. Air. Soil Pollut.* **223**, 3729–3738.

Paria, S. 2008 Surfactant-enhanced remediation of organic contaminated soil and water. *Adv. Colloid Interface Sci.* **138**, 24–58.

Park, J. H., Choppala, G. K., Bolan, N. S., Chung, J. W. & Chuasavathi, T. 2011 Biochar reduces the bioavailability and phytotoxicity of heavy metals. *Plant Soil* **348**, 439–451.

Parshetti, G. K., Kent Hoekman, S. & Balasubramanian, R. 2013 Chemical, structural and combustion characteristics of carbonaceous products obtained by hydrothermal carbonization of palm empty fruit bunches. *Bioresour. Technol.* **135**, 683–689.

Pavlovič, I., Knez, Ž & Škerget, M. 2013 Hydrothermal reactions of agricultural and food processing wastes in sub- and supercritical water: A review of fundamentals, mechanisms, and state of research. *J. Agric. Food Chem.* **61**, 8003–8025.

Pilon, G. & Lavoie, J. M. 2011 Characterization of switchgrass char produced in torrefaction and pyrolysis conditions. *BioResources* **6**, 4824–4839.

Qambrani, N. A., Rahman, M. M., Won, S., Shim, S. & Ra, C. 2017 Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: A review. *Renewable Sustainable Energy Rev.* **79**, 255–273.

Qian, K., Kumar, A., Zhang, H., Bellmer, D. & Huhnke, R. 2015 Recent advances in utilization of biochar. *Renewable Sustainable Energy Rev.* **42**, 1055–1064.

Qiu, Y., Zheng, Z., Zhou, Z. & Sheng, G. D. 2009 Effectiveness and mechanisms of dye adsorption on a straw-based biochar. *Bioresour. Technol.* **100**, 5348–5351.

Rajapaksha, A. U., Vithanage, M., Zhang, M., Ahmad, M., Mohan, D., Chang, S. X. & Ok, Y. S. 2014 Pyrolysis condition affected sulfamethazine sorption by tea waste biochars. *Bioresour. Technol.* **166**, 303–308.

Rajapaksha, A. U., Chen, S. S., Tsang, D. C. W., Zhang, M., Vithanage, M., Mandal, S., Gao, B., Bolan, N. S. & Ok, Y. S. 2016 Engineered/designer biochar for contaminant removal/immobilization from soil and water: Potential and implication of biochar modification. *Chemosphere* **148**, 276–291.

Regmi, P., Garcia Moscoso, J. L., Kumar, S., Cao, X., Mao, J. & Schafran, G. 2012 Removal of copper and cadmium from aqueous solution using switchgrass biochar produced via hydrothermal carbonization process. *J. Environ. Manage.* **109**, 61–69.

Sajjadi, B., Chen, W. Y. & Egiebor, N. O. 2019 A comprehensive review on physical activation of biochar for energy and environmental applications. *Rev. Chem. Eng.* **35**, 735–776.

Saleh, M. M. 2006 On the removal of cationic surfactants from dilute streams by granular charcoal. *Water Res.* **40**, 1052–1060.

Samsuri, A. W., Sadegh-Zadeh, F. & Seh-Bardan, B. J. 2013 Adsorption of As(III) and As(V) by Fe coated biochars and biochars produced from empty fruit bunch and rice husk. *J. Environ. Chem. Eng.* **1**, 981–988.

Senelwa, K. & Sims, R. E. H. 1999 Fuel characteristics of short rotation forest biomass. *Biomass and Bioenergy* **17**, 127–140.

Shafizadeh, F. 1982 Introduction to pyrolysis of biomass. *J. Anal. Appl. Pyrolysis* **3**, 283–305.

Sivula, L., Oikari, A. & Rintala, J. 2012 Toxicity of waste gasification bottom ash leachate. *Waste Manag.* **32**, 1171–1178.

Somyanonthanakun, W., Nakarungsee, P., Junpirom, S., Yingsamphancharoen, T. & Thongmee, S. 2016 Development of activated carbon from bagasse for adsorbing heavy metals. *Proc. Int. Soc. Sugar Cane Technol.* **29**, 1416–1423.

Song, Z., Lian, F., Yu, Z., Zhu, L., Xing, B. & Qiu, W. 2014 Synthesis and characterization of a novel MnOx-loaded biochar and its adsorption properties for Cu2 + in aqueous solution. *Chem. Eng. J.* **242**, 36–42.

Suliman, W., Harsh, J. B., Abu-Lail, N. I., Fortuna, A. M., Dallmeyer, I. & Garcia-Perez, M. 2016 Influence of feedstock source and pyrolysis temperature on biochar bulk and surface properties. *Biomass and Bioenergy* **84**, 37–48.

Sun, K., Keiluweit, M., Kleber, M., Pan, Z. & Xing, B. 2011 Sorption of fluorinated herbicides to plant biomass-derived biochars as a function of molecular structure. *Bioresour. Technol.* **102**, 9897–9903.

Sun, Y., Gao, B., Yao, Y., Fang, J., Zhang, M., Zhou, Y., Chen, H. & Yang, L. 2014 Effects of feedstock type, production method, and pyrolysis temperature on biochar and hydrochar properties. *Chem. Eng. J.* **240**, 574–578.

Tan, Z., Qiu, J., Zeng, H., Liu, H. & Xiang, J. 2011 Removal of elemental mercury by bamboo charcoal impregnated with H_2O_2. *Fuel* **90**, 1471–1475.

Tan, G., Mao, Y., Wang, H. & Xu, N. 2020 A comparative study of arsenic(V), tetracycline and nitrate ions adsorption onto magnetic biochars and activated carbon. *Chem. Eng. Res. Des.* **159**, 582–591.

Tchomgui-Kamga, E., Alonzo, V., Nanseu-Njiki, C. P., Audebrand, N., Ngameni, E. & Darchen, A. 2010 Preparation and characterization of charcoals that contain dispersed aluminum oxide as adsorbents for removal of fluoride from drinking water. *Carbon N. Y.* **48**, 333–343.

Tomczyk, A., Boguta, P. & Sokołowska, Z. 2019 Biochar efficiency in copper removal from Haplic soils. *Int. J. Environ. Sci. Technol.* **16**, 4899–4912.

Tomczyk, A., Sokołowska, Z. & Boguta, P. 2020 Biochar physicochemical properties: Pyrolysis temperature and feedstock kind effects. *Rev. Environ. Sci. Biotechnol.* **19**, 191–215.

Tran, H. N., You, S. J. & Chao, H. P. 2016 Effect of pyrolysis temperatures and times on the adsorption of cadmium onto orange peel derived biochar. *Waste Manage. Res.* **34**, 129–138.

Uchimiya, M., Klasson, K. T., Wartelle, L. H. & Lima, I. M. 2011a Influence of soil properties on heavy metal sequestration by biochar amendment: 1. Copper sorption isotherms and the release of cations. *Chemosphere* **82**, 1431–1437.

Uchimiya, M., Wartelle, L. H., Klasson, K. T., Fortier, C. A. & Lima, I. M. 2011b Influence of pyrolysis temperature on biochar property and function as a heavy metal sorbent in soil. *J. Agric. Food Chem.* **59**, 2501–2510.

Uchimiya, M., Bannon, D. I., Wartelle, L. H., Lima, I. M. & Klasson, K. T. 2012 Lead retention by broiler litter biochars in small arms range soil: impact of pyrolysis temperature. *J. Agric. Food Chem.* **60**, 5035–5044.

Usman, A., Sallam, A., Al-Omran, A., El-Naggar, A., Alenazi, K., Nadeem, M. & Al-Wabel, M. 2013 Chemically modified biochar produced from conocarpus wastes: An efficient sorbent for Fe(II) removal from acidic aqueous solutions. *Adsorpt. Sci. Technol.* **31**, 625–640.

Verheijen, S., Jeffery, A. C. B., van der Velde, M. & Diafas, I. 2009 *Biochar Application to Soils*.

Vithanage, M., Rajapaksha, A. U., Zhang, M., Thiele-Bruhn, S., Lee, S. S. & Ok, Y. S. 2015 Acid-activated biochar increased sulfamethazine retention in soils. *Environ. Sci. Pollut. Res.* **22**, 2175–2186.

Wan, Z. & Li, K. 2018 Effect of pre-pyrolysis mode on simultaneous introduction of nitrogen/oxygen-containing functional groups into the structure of bagasse-based mesoporous carbon and its influence on Cu(II) adsorption. *Chemosphere* **194**, 270–370.

Wang, Y. & Liu, R. 2018 H2o2 treatment enhanced the heavy metals removal by manure biochar in aqueous solutions. *Sci. Total Environ.* **628–629**, 1139–1148.

Wang, J. & Wang, S. 2019 Preparation, modification and environmental application of biochar: A review. *J. Cleaner Prod.* **227**, 1002–1022.

Wang, Y., Wang, X. J., Liu, M., Wang, X., Wu, Z., Yang, L. Z., Xia, S. Q. & Zhao, J. F. 2012 Cr (VI) removal from water using cobalt-coated bamboo charcoal prepared with microwave heating. *Ind. Crops Prod.* **39**, 81–88.

Wang, M. C., Sheng, G. D. & Qiu, Y. P. 2015a A novel manganese-oxide/biochar composite for efficient removal of lead(II) from aqueous solutions. *Int. J. Environ. Sci. Technol.* **12**, 1719–1726.

Wang, S. H., Stevenson, K. B., Hines, L., Mediavilla, J. R., Khan, Y., Soni, R., Dutch, W., Brandt, E., Bannerman, T., Kreiswirth, B. N. & Pancholi, P. 2015b Evaluation of repetitive element polymerase chain reaction for surveillance of methicillin-resistant Staphylococcus aureus at a large academic medical center and community hospitals. *Diagn. Microbiol. Infect. Dis.* **81**, 13–17.

Weber, K. & Quicker, P. 2018 Properties of biochar. *Fuel* **217**, 240–261.

Wiedner, K., Rumpel, C., Steiner, C., Pozzi, A., Maas, R. & Glaser, B. 2013 Chemical evaluation of chars produced by thermochemical conversion (gasification, pyrolysis and hydrothermal carbonization) of agro-industrial biomass on a commercial scale. *Biomass Bioenergy* **59**, 264–278.

Wornat, M. J., Hurt, R. H., Yang, N. Y. C. & Headley, T. J. 1995 Structural and compositional transformations of biomass chars during combustion. *Combust. Flame* **100**, 131–143.

Xie, T., Reddy, K. R., Wang, C., Yargicoglu, E. & Spokas, K. 2015 Characteristics and applications of biochar for environmental remediation: A review. *Crit. Rev. Environ. Sci. Technol.* **45**, 939–969.

Xiong, Z., Shihong, Z., Haiping, Y., Tao, S., Yingquan, C. & Hanping, C. 2013 Influence of NH_3/CO_2 modification on the characteristic of biochar and the CO2 capture. *Bioenergy Res.* **6**, 1147–1153.

Xu, R. k., Xiao, S. c., Yuan, J. h. & Zhao, A. z. 2011 Adsorption of methyl violet from aqueous solutions by the biochars derived from crop residues. *Bioresour. Technol.* **102**, 10293–10298.

Xu, T., Lou, L., Luo, L., Cao, R., Duan, D. & Chen, Y. 2012 Effect of bamboo biochar on pentachlorophenol leachability and bioavailability in agricultural soil. *Sci. Total Environ.* **414**, 727–731.

Xue, Y., Gao, B., Yao, Y., Inyang, M., Zhang, M., Zimmerman, A. R. & Ro, K. S. 2012 Hydrogen peroxide modification enhances the ability of biochar (hydrochar) produced from hydrothermal carbonization of peanut hull to remove aqueous heavy metals: Batch and column tests. *Chem. Eng. J* **200–202**, 673–680.

Yaashikaa, P. R., Kumar, P. S., Varjani, S. & Saravanan, A. 2020 A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. *Biotechnol. Reports* **28**, e00570.

Yakkala, K., Yu, M. R., Roh, H., Yang, J. K. & Chang, Y. Y. 2013 Buffalo weed (Ambrosia trifida L. var. trifida) biochar for cadmium (II) and lead (II) adsorption in single and mixed system. *Desalin. Water Treat.* **51**, 7732–7745.

Yang, G. X. & Jiang, H. 2014 Amino modification of biochar for enhanced adsorption of copper ions from synthetic wastewater. *Water Res.* **48**, 396–405.

Yang, H., Yan, R., Chin, T., Liang, D. T., Chen, H. & Zheng, C. 2004 Thermogravimetric analysis – Fourier transform infrared analysis of palm oil waste pyrolysis. *Energy Fuels* **18**, 1814–1821.

Yang, Z. H., Xiong, S., Wang, B., Li, Q. & Yang, W. C. 2013 Cr(III) adsorption by sugarcane pulp residue and biochar. *J. Cent. South Univ.* **20**, 1319–1325.

Yao, Y., Gao, B., Inyang, M., Zimmerman, A. R., Cao, X., Pullammanappallil, P. & Yang, L. 2011 Removal of phosphate from aqueous solution by biochar derived from anaerobically digested sugar beet tailings. *J. Hazard. Mater.* **190**, 501–507.

Yao, Y., Gao, B., Chen, J. & Yang, L. 2013 *Engineered Biochar Reclaiming Phosphate From Aqueous Solutions: Mechanisms and Potential Application as A Slow-Release Fertilizer.*

Yao, Y., Gao, B., Fang, J., Zhang, M., Chen, H., Zhou, Y., Creamer, A. E., Sun, Y. & Yang, L. 2014 Characterization and environmental applications of clay-biochar composites. *Chem. Eng. J.* **242**, 136–143.

Yong, S. K., Bolan, N., Lombi, E. & Skinner, W. 2013 Synthesis and characterization of thiolated chitosan beads for removal of Cu(II) and Cd(II) from wastewater. *Water. Air. Soil Pollut.* **224**, 1–12.

Yu, L., Tang, J., Zhang, R., Wu, Q. & Gong, M. 2013 Effects of biochar application on soil methane emission at different soil moisture levels. *Biol. Fertil. Soils* **49**, 119–128.

Yu, X. Y., Ying, G. G. & Kookana, R. S. 2009 Reduced plant uptake of pesticides with biochar additions to soil. *Chemosphere* **76**, 665–671.

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

Zech, W., Haumaier, L. & Hempfling, R. 2015 Ecological aspects of soil organic matter in tropical land use. *Humic Subst. Soil Crop Sci. Sel. Readings* **8**, 187–202.

Zhang, H., Lin, K., Wang, H. & Gan, J. 2010 Effect of Pinus radiata derived biochars on soil sorption and desorption of phenanthrene. *Environ. Pollut.* **158**, 2821–2825.

Zhang, M., Gao, B., Yao, Y., Xue, Y. & Inyang, M. 2012 Synthesis of porous MgO-biochar nanocomposites for removal of phosphate and nitrate from aqueous solutions. *Chem. Eng. J.* **210**, 26–32.

Zhang, X., Wang, H., He, L., Lu, K., Sarmah, A., Li, J., Bolan, N. S., Pei, J. & Huang, H. 2013 Using biochar for remediation of soils contaminated with heavy metals and organic pollutants. *Environ. Sci. Pollut. Res.* **20**, 8472–8483.

Zheng, W., Guo, M., Chow, T., Bennett, D. N. & Rajagopalan, N. 2010 Sorption properties of greenwaste biochar for two triazine pesticides. *J. Hazard. Mater.* **181**, 121–126.

Zheng, Y., Wang, J., Li, D., Liu, C., Lu, Y., Lin, X. & Zheng, Z. 2021 Insight into the $KOH/KMnO_4$ activation mechanism of oxygen-enriched hierarchical porous biochar derived from biomass waste by in-situ pyrolysis for methylene blue enhanced adsorption. *J. Anal. Appl. Pyrolysis* **158**, 14–16.

Zhou, Y., Gao, B., Zimmerman, A. R., Fang, J., Sun, Y. & Cao, X. 2013 Sorption of heavy metals on chitosan-modified biochars and its biological effects. *Chem. Eng. J.* **231**, 512–518.

Zuo, S., Yang, J., Liu, J. & Cai, X. 2009 Significance of the carbonization of volatile pyrolytic products on the properties of activated carbons from phosphoric acid activation of lignocellulosic material. *Fuel Process. Technol.* **90**, 994–1001.