Biochar in water and wastewater treatment

- A sustainability Assessment

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Abstract

Innovation of sustainable materials that are efficient, economic, environmentally friendly, and socially acceptable for real-scale environmental applications is currently a trend in the scientific community. Recently, biochar as one of the main pyrogenic products from thermo-chemical process of ligno-cellulosic biomass has been widely studied to deal with water pollutants and wastewaters. Thus, there is an urgent need for the assessment of developed technologies to promote commercialization of the most sustainable technologies in order to identify the existing technical gaps. This review aims to identify the current trends in the literature and to evaluate the technology against sustainability considerations, emphasizing on the recently published reviews as well as the highly cited papers. The existing gaps and recommendations for future studies is discussed.

***Keywords**: Biochar; environmental contaminants; sustainability; water and wastewater treatment.*

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Nomenclature

AEC	Anion Exchange Capacity	MRT	Mean Residence Time
AMBC	Amino Grafted Biochar	MFCs	Microbial Fuel Cells
AO7	Acid Orange	PAHs	Polycyclic Aromatic Hydrocarbons
AOPs	Advanced Oxidation Processes	PMS	Peroxymonosulfate
AWC	Available Water Content	PNEC	Predicted No-Effect Concentration
BC	Biochar	POPs	Persistent Organic Pollutants
BG	Sugarcane bagasse	PPCPs	Pharmaceutical and personal care products
B-SC	Burning and Soil Covering	PS	Persulfate
BPA	Bisphenol A	PZSE	Point of Zero Salt Effect
BES	Bioelectrochemical System	PZNC	Point of zero net charge
CB	Corn-Straw-Derived BC	SBC	Sludge-Derived Biochar
CEC	Cation Exchange Capacity	SIN	Soil Inorganic Nitrogen
COD	Chemical Oxygen Demand	SMT	Sulfamethazine
COCs	Chlorinated Organic Compounds	SOC	Soil Organic Carbon
CSPS	Concentrated Solar Power System	SCG	Spent Coffee Grounds
CV	Crystal Violet	SSA	Specific Surface Area
DOC	Dissolved Organic Carbon	STF	Structural Functionalization
DOM	Dissolved Organic Matter	SWR	Soil Washing Residue
EC	Electrical conductivity	TCLP	Toxicity Characteristic Leaching Procedure
FMBC	Fe-Mn Modified Biochar Composite	TCS	Triclosan
GHGs	Greenhouse Gases	TOC	Total Organic Carbon
GWP	Global Warming Potential	VLI	Visible Light Irradiation
HB	Hardwood-Derived Biochar	VOCs	volatile organic compounds
HMs	Heavy Metals	WHC	Water Holding Capacity
HTC	Hydro-Thermal Carbonization	WoS	Web of Science
LCA	Life-Cycle Assessment	W&W	Water and Wastewater
MB	Methylene Blue	VOCs	Volatile Organic Compounds
M-BC	Magnetic Biochar		

Contents

1. Introduction

Various biological and physicochemical methods have been developed to treat polluted water and wastewater (W&W) and to provide efficient and economic options for industries to deal with their effluents and satisfy the stringent environmental regulations [1]. Biological treatments including the activated sludge process [2] and anaerobic digestion [3,4] are low-cost [5] and efficient options to deal with low to moderate strength effluents and are widely applied [6]. However, some limitations are the unsatisfactory removal of some non-biodegradable pollutants that are of emerging concern [7,8] and the high costs related to the management of the sludge generated. Therefore, physicochemical treatment techniques such as ultrasonic irradiation [9–11] and microwave irradiation [12,13] and chemical treatments such as Fenton-like oxidation processes [14,15] and catalytic decomposition of organic pollutants (especially with advanced engineered nanomaterials) [16,17] via advanced oxidation processes (AOPs) have been developed and implemented in the recent decades. Also adsorption methods are of high interest for the removal of organic and inorganic compounds [18,19]. Carbonaceous materials such as activated carbon [20–22] are primarily applied.

There are pieces of evidence in the literature that activated carbon, especially those produced from agricultural residues are low-cost and efficient materials to deal with various organic [23] and inorganic [24,25] pollutants. In this regard, there has been also a trend for the development of other types of carbonaceous materials which can satisfy the sustainability requirements to be applied for real-scale applications [26]. Efforts have been also made to identify and prioritize sustainability criteria for novel environmental remediation technologies [27] to cover relevant technical, environmental, economic, and social considerations [28].

Biochar (BC) is the carbon rich solid derived from pyrolysis of biomass under oxygen-free (or low oxygen content) conditions and at temperatures above 250°C. Currently, the production of BC from biomass is considered as an option for carbon capture and storage (CCS) in order to mitigate adverse environmental consequences arising from CO_2 accumulation in the atmosphere leading to climate change [29,30]. Its high carbon content and large specific surface area (SSA) [31–33] have, moreover, made BC a valid candidate for a variety of environmental applications such as soil amendment [34–37]. Numerous published reports confirm the advantages of BC for environmental applications [38–40]. BC has been widely studied to remove organic and inorganic environmental contaminants, where it is used as an adsorbent for the immobilization of toxic elements such as heavy metals (HMs) [38,39,41,42] and as a catalyst in advanced oxidation processes (AOPs) to degrade toxic pollutants [43] such as complex organic compounds [44]. The production and application of BC for various environmental applications have been studied extensively over the past few decades and numerous papers have reported on modifications of the physicochemical properties of BC to enhance its functionality both on laboratory and pilot scale.

The present review provides an overview on the global efforts made on the production of BC for W&W treatment applications and evaluates the technology against the sustainability criteria. Current trends have been identified emphasizing on high quality reviews published in recent years and highly cited papers. The results provide a critical overview of the scientific state-of-the-art in this field and identify the existing knowledge gaps in order to direct future studies in this field.

2. Pyrolysis for BC production: an overview

Various thermochemical processes have been developed to convert biomass into BC together with other products such as bio-oil and non-condensable gases, including hydro-thermal carbonization (HTC), pyrolysis, and gasification [45]. Under an oxygen free environment, biomass is converted to BC under relatively high temperatures (Table 1). Under these conditions, the main constituents of biomass (cellulose, hemicelluloses, and lignin) undergo depolymerization and fragmentation [46]. The relative proportion of the pyrolysis products (BC, bio-oil and syngas) is primarily dependent on the reactor configuration and pyrolysis conditions [47]. Currently, there is a trend to improve the quality of produced BC by the optimization of BC production conditions, especially for agricultural and environmental applications [48,49].

Pyrolysis can be performed under slow (conventional) and fast conditions. Slow pyrolysis has been used for thousands of years to produce charcoal [50–52]. When a relatively long residence time (above 2 h) is applied for the conversion of biomass to BC, the process is generally called slow pyrolysis. BC, bio-oil, and gas are produced during this process in almost the same ratio irrespective of the type of biomass and the process is performed under atmospheric pressure using various types of reactors [53].

Slow pyrolysis conditions generally result in a relatively high BC yield [54]. The BC contains a high concentration of lignin and ash. Thus produced BC has a relatively large particle size [55]. Alternatively, when biomass is subjected to relatively high temperatures (500-1000°C) for a low residence time , the process is called fast pyrolysis [33]. High yields of bio-oil and non-condensable gases are formed in this process and the yield of BC is relatively low compared to slow pyrolysis [56]. The bio-oil produced in this process is generally applied as a liquid fuel and as precursor for the production of bio-based chemical building blocks [57–60]. The composition of the bio-oil is largely determined by the origin of the biomass and the operational parameters during pyrolysis of biomass. For fast pyrolysis, biomass is normally pre-dried (to less than 10% water content). BC prepared by fast pyrolysis is characterized by a high concentration of recalcitrant aromatic structures depending on the applied process parameters [61].

Inherent metallic compounds can also alter the properties of the BC during the pyrolysis process, as discussed in detail by Giudicianni et al., [62]. Cations such as potassium, sodium, calcium, magnesium, iron, and aluminium cations as well as inorganics such as sulfur, phosphorous, and chlorine are generally present in the plant tissues. As a general rule, silicon, phosphorous, and aluminium can inhibit the reactivity of the biochar through their reaction with metals (especially alkaline earth metals) resulting in the formation of silicates, phosphates, and aluminates during the thermal treatment of biomass [63]. By increasing the pyrolysis temperature (≥ 700 °C) heteroatoms are removed and charring reactions result in the growth of the graphene layer and the aromaticity of the biochar. Protein decomposition at temperatures below 500 °C is also responsible for the release of sulfur from the char content. However, a part of this element reacts with metallic elements such as Ca and K (to form CaS and K_2S, respectively), and remains in the biochar content [64]. In addition, alkaline earth metals can slightly catalyse the cleavage of N-containing compounds NH_3 and HCN [65]. Large molecules including heteroatoms can prevent closing the graphene-like layers at low temperatures resulting in the formation of micropores. However, the presence of alkaline earth metals depresses the formation of such molecules resulting in the reduction in the porosity of the biochar. Also, metallic elements favour the growth of the biochar at higher temperatures with low specific surface area [62].

Gasification is another thermochemical process in which organic matter converted to hydrogen gas (H_2), carbon dioxide (CO_2), carbon monoxide (CO), and low amounts of hydrocarbons such as methane

(CH_4) [66–68]. Gasification is conducted under a controlled oxygen environment at high temperatures, ranging from 700 to 800 °C [69]. Gaseous components are the predominant products, followed by BC (around 10%) and finally liquid products in very low quantities [69]. The composition of produced gas depend on process conditions [70] and the medium (oxygen, air or stream) used to introduce the oxygen in the reaction system. The gas has various energetic applications, such as in gas turbines and gas engines [71]. The type of feedstock, the peak temperature, and the rate of temperature increase during pyrolysis are the main variables that determine the properties of BC including surface area, porosity, morphology, elemental composition, pH, and conductivity [72].

Recent studies have highlighted the impact of feedstock on properties of BC such as surface complexation and ability to adsorb heavy metals [71–74], mechanical properties [77], carbon fraction [78], and particulate matter and polycyclic aromatic hydrocarbon content [79]. Temperature is a second factor affecting BC properties, determining the elemental composition of the BC prepared. For instance, Yuan et al., [80] applied pyrolysis process for BC production from sewage sludge at temperatures between 300 and 700°C. Extraction of water soluble contents indicated that BC prepared in the higher temperature range contained a lower concentration of nitrogen, but was rich in phosphorus and potassium. Some observed effects of pyrolysis temperature on BC properties are summarized in Table 1.

Table 1. Effects of BC production temperature on its properties.

BC type	Condition	Main properties	Ref.
Whitewood BC	High-temperature produced wood BC	Absence of acidic functional groups[a]	[81]
Corn stover, red oak BC	BC prepared under moderate temperature (500°C)	High CEC, but low AEC, PZSE and PZNC values	[82]
	BC prepared under high temperature (700°C)	Low CEC and high AEC, PZSE and PZNC values	
Coppiced woodlands BC	High-temperature crop residue and manure BC	High ash content	[83]
Sugarcane bagasse (BG) BC	Pyrolysis temperature from 300 °C to 600 °C	Decrease in average pore diameter of produced BCs with increasing pyrolysis temperature	
Cow manure-loaded BC BC	Low-temperature BCs	Presence of volatile organic compounds (VOCs), which inhibit microbial activity	[80,84]
Pitch pine (Pinusrigida) BC	Increasing pyrolysis temperature from 300°C to 500°C	Decrease in BC yield from 60.7% to 14.4%	[85]
Miscanthus BC	Pyrolysis temperature above 360°C	High thermal and biological resistance to degradation	[86]
Hardwood (oak [*Quercus*])-based wood pellets	Pyrolysis temperature from 400°C to 600°C	Increased temperature leads to the conversion of labile C forms to aromatic C structures in BC	[87]
Boiled radix isatidis residue BC	Pyrolysis temperature from 300°C to 700 ◦C	Increasing temperature results in a reduction of volatile matter content, strengthens the carbon enrichment, and increasing the aromatic organic compounds	[88]

a) The BC has lost most of the acidic functional groups during high-temperature pyrolysis.
b) They generally have stable forms of carbon as well as high C/N ratio.

In many situations, the conversion of solid waste to BC satisfies the sustainability requirements. For instance, sewage sludge as an organic waste with a high level of nitrogen, phosphorous, and micronutrients is produced in a wastewater treatment plant, which needs an efficient management strategy to avoid subsequent environmental issues [89].

3. BC for W&W treatment: Sustainability considerations

In recent years, a surge of interest has occurred towards the production of BC as a valuable material obtained from biomass valorisation via pyrolysis. On the other hand, global concerns on water pollution and the problems associated with the production and discharge of huge amounts of industrial effluents [25], [88, 89] have motivated research efforts to explore efficient and cost-effective methods to deal with these issues. As such, BC has been introduced as a promising candidate to deal with W&W polluted with both conventional and emerging contaminants. In this section, various sustainability considerations [28] for the treatment of polluted W&W using BC are discussed along with the current trends and existing knowledge gaps.

3.1 Technical considerations

The parameters that determine the technical feasibility of BC for the treatment of polluted W&W include treatment efficiency, process stability, scale-up capability, combination with other W&W techniques, ease of implementation as well as health and safety related aspects.

3.1.1 Efficiency

3.1.1.1 Nutrient removal

BC has been studied as an adsorbent for the removal of nutrients through adsorption [92–94]. The adsorption capacity of BC is highly dependent on its surface chemistry, specific surface area, porosity, and shape. Many efforts have been done to study of effects of functional groups that are present at the BC surface on the adsorption of nutrients. Process conditions during pyrolysis (mainly temperature) and the properties of the feedstock largely affect the type and abundance of functional groups at the BC surface [95]. Banik et al., [82] studied the influence of parameters such as the type of feedstock, pyrolysis temperature, characteristics of reaction medium, operating pH and the effects of treating the feedstock with aluminum chloride ($AlCl_3$) before pyrolysis on the produced BC anion exchange capacity (AEC), cation exchange capacity (CEC), zero net charge (PZNC) and point of zero salt effect (PZSE). The authors suggested that the BC prepared at 500°C demonstrated high CEC, but low AEC, PZSE and PZNC. This was mainly explained by the presence of negative charges on the surface of BC, resulting from the carboxylate and phenolate functional groups. Another study [96] has demonstrated that any increase in pyrolysis temperature potentially leads to BC with low CEC and high AEC, PZSE and PZNC, resulting from the positive surface charge of the produced BCs that originated from the presence of non-hydrolysable bridging oxonium (oxygen heterocycles) groups. Also, BC with an $AlCl_3$ pre-treatment demonstrated high AEC, PZSE, and PZNC due to variably charged aluminol groups onto the BC surface. BC with positive surface charges demonstrated a high capability for adsorption of cationic contaminants [97,98]. However, other factors (such as feedstock type) are also involved in the determination of BC properties, including yield, pH, CEC, SSA, ash content, and elemental composition [99]. Also, the operating conditions influence the treatment efficiency. For instance, Fidel et al., [100] demonstrated that the adsorption capability of BC prepared from red oak and corn stover at three pyrolysis temperatures (400, 500 and 600 °C) is highly dependent on the electrostatic and pH of ammonium and nitrate sorption.

To enhance the tendency of BC to adsorb anions, structural functionalization (STF) of BC has been recognized to be effective. STF can be performed in a target-oriented way to tailor the specificity of BC for the adsorption of specific nutrients [101]. Impregnation of metal oxides or metal salts into BC has been reported as an effective strategy to prepare BC with the desired properties. Various metallic compounds such as magnesium-impregnated BC [102] have been used for the removal of nutrients such as phosphate.

Some literature reports have demonstrated on various improvements in BC capabilities such as anion adsorption capacity and magnetic properties as a result of impregnation with magnetic particles to form magnetic BC (M-BC) [103]. For instance, Micháleková-Richveisová et al., [104] improved the adsorption of anionic forms of phosphate after impregnation with Fe via direct hydrolysis of $Fe(NO_3)_3$. Although the specific surface area of the BC decreased due to filling of the pores with Fe, the sorption capacity (Q_{max}) of the BC increased considerably (by a factor of 12-50). The authors also demonstrated the pH dependency of the adsorption process (optimum pH=4.5–5.5) and initial material dosage, as confirmed by other studies [105,106]. In order to meet the sustainability criteria from a technical, economic, environmental and social perspective, studies have been carried out using natural containing iron precursors (iron-enriched plants) to prepare the magnetic BC [107]. Some comparative studies have also evaluated the efficiency of magnetic impregnated BC with those impregnated with other elements. Choi et al., [108] found a higher maximum adsorption capacity for BC impregnated with Ca compared to those impregnated with iron oxide and zinc oxide, but still lower than those impregnated by CaO and MgO. In spite of the lower efficiency of M-BC, the ability to easily recover and reuse the BC adsorbent still makes it a good alternative.

Generally, there are a number of environmental pollutants in the context of polluted waters and wastewaters. Hence, in case the biochar has the capability for the removal of various pollutants simultaneously (Fig. 1) it can be used as the sole treatment technique to reach the desired treatment efficiencies. Recent studies have explored the efficiency of BC products for simultaneous removal of different nutrients from the polluted effluents. Li et al., [109] succeeded in the simultaneous removal of nutrients including ammonium and phosphate and some organics from swine effluents using MgO impregnated BC, demonstrating optimum adsorption capacities of 398 mg/g, 22 mg/g and 247 mg/g for phosphate, ammonium, and humate, respectively. Other reports on the simultaneous removal of nutrients from aqueous media [105,106] have demonstrated the applicability of BC to deal with a wide range of nutrients.

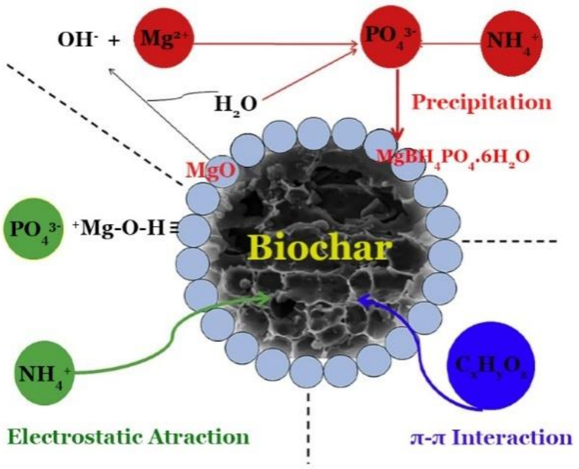

Fig. 1. A schematic representation of the mechanisms involved in simultaneous adsorption of nutrients by the BC particles, adopted from Li et al., [109].

Table 2 presents a summary of the main findings and conclusions of recently published reviews on the application of BC for nutrient removal from aqueous media.

Table 2. Summary of results and conclusions achieved by recently published review papers on the application of BC for nutrient removal from the aqueous media.

Subject	Findings/ Remarks	Ref.
Involved mechanism	Multiple mechanisms are involved in the adsorption of nitrates and phosphates onto the BC including physical (related to surface area of BC) and chemical (related to the type of BC and functionalization) capturing phenomena.	[112]
New fields of application	The potential of BC for the removal of nutrients can demonstrate the applicability of BC for upgrading the existing wastewater treatment plants (WWTPs) for nitrogen (as NH_4^+–N and NO_3^-N) removal in winter, when nitrifying and denitrifying bacteria are accumulated at low temperatures.	[113]

Manipulation in the BC properties	Pristine BCs are not generally suitable for the adsorption of anions. Measures such as surface functionalization can promote their efficiency towards nutrients.	[114]
	Among the various functionalization methods, physical methods such as steam activation are less effective for improving the BC surface functionality compared with chemical methods, especially alkali-treated BC. Acidic treatment can provide more oxygenated functional groups on the surface of BC.	[115]
Recommendations for further studies	The cross influence of different nutrients in the overall adsorption process as well as simultaneous adsorption of various nutrients onto BC need to be studied.	[112]

Biochar-based electrodes have been also developed in very recent studies in order to adsorb inorganic compounds from the aqueous media. Yao et al., [116] indicated that doping the nitrogen to the loofah sponge-derived biochar (as the cathode) not only increased the adsorption capacity of bromate by the electrode, but also could facilitate the electron transfer, resulting in the high electrocatalytic removal of the nutrient.

3.1.1.2 Heavy metals

Removal of heavy metals from polluted W&W streams using BC has received large attention in recent years mainly due to the toxic nature of heavy metals (HMs) and their impact on the ecosystem and human health [111,112]. The low efficiency of the conventional treatment methods [117] to treat this type of toxic W&W has led to recent developments on the use of BC for the removal of HM, thereby demonstrating more efficient and economically feasible options than activated carbon, especially for chromium and zinc [25,119]. Efforts have been made to explore the efficiency of various types of BC towards the removal of HM from polluted streams. Some pristine BC have demonstrated acceptable performance such as the use of Japanese oak wood-derived BC used by Khan et al., [120] for sorption studies on arsenite (As(III)) and arsenate (As(V)). These results indicated slightly higher adsorption of As(V) compared to As(III) (84 and 81%, respectively). Modifications of BC have extended their capabilities to deal with HMs. As can be seen Table 3, various types of BC have exhibited varying performances (from low to high) for the removal of HM from polluted W&W. In fact, the removal of HM is correlated with the origin of BC, its modifications and experimental conditions.

It is well understood that pyrolysis temperature determines the adsorptive capability of BC for HMs. Perilla leaf-derived BCs produced at 300 and 700°C have been studied by Burton et al., [121] to find that the BC prepared at 700°C was more effective than that prepared at 300°C, especially for the removal of As (III) compared to As (V). They concluded that the higher specific surface area of BC prepared at 700°C and its surface aromaticity favoured the adsorption of As compared to BC prepared at 300°C. State-of-the-art reviews have also added valuable information on the removal of HM using

BC. For instance, Ahmed et al., [115] reviewed the application of modified BC for the treatment of W&W to arrive the conclusion that methods such as steam activation may not improve the properties of BC for such purposes. They concluded that chemical modification is a better option. Alkali-treatment and impregnation with nanomaterials have demonstrated to be the most efficient techniques to enhance the adsorption capacity for environmental contaminants [115]. In principal, functional groups (such as –OH, -COOH, -C-O, -CH_3) onto the surface of BC are responsible for the surface complexation (and precipitation) of the contaminants resulting in their removal from the aqueous media (Fig. 2) [120].

Table 3. Various types of BC and their potential for the adsorption of HM.

Metal ions	BC Type	BC Origin	BC preparation conditions	Adsorption capacity (mg/g)	Authors
Pb^{2+}	Pristine	Pine wood char	Fast pyrolysis at 400-450°C	4.13	Mohan et al., [122]
	Pristine	Dairy manure BC	At 200-350°C	132.81	Cao et al., [123]
	Pristine	Buffalo Weed BC	At 300, 500 and 700°C	333.33 (700°C)	Yakkala et al., [124]
Cd^{2+}	Pristine	Municipal sewage sludge BC	At 900°C	20 (at pH≤2) 40 (at pH>3)	Tan et el., [125]
	Modified	Corn stalk BC supported nZVI	At 500°C	33.81	Yang et al., [126]
	Pristine	Cow manure BC	At 400 and 600°C	118.40	Kołodyńska et al., [127]
As^{3+}	Pristine	Pine wood char	400–450°C	1.20	Mohan et al., [122]
	Modified	Fe-modified Rice straw BC	Fast pyrolysis 450°C.[a]	26.9	Nham et al., [128]
	Modified	Iron oxide nano-needle array-decorated cotton fiber BC	Pyrolysis at 800°C.[b]	70.22	Wei et al., [129]
Cu^{2+}	Pristine	Soybean straw char	At 400 °C	0.03	Tong et al., [130]
		Dairy manure BC	At 200°C and 350°C	48.41 (350°C)	Xue et al., [131]
	Modified	Ferromanganese binary oxide-BC composites	At 600°C	64.9	Zhou et al., [132]
Zn^{2+}	Pristine	Hard wood char	At 450°C and 600°C	4.54 (600°C)	Chen et al., [133]
	Pristine	*Chlorella sp.* residue BC	At 500 °C	17.62	Amin et al., (2017) [134]
	Pristine	Dairy manure BC	At 200°C and 350°C	32.95 (350°C)	Xue et al., [131]
Ni^{2+}	Pristine	Taihu blue algae BC	At 800°C	2.2	Wang et al., [135]
	Pristine	Chlorella sp. residue BC	At 450°C	27.45	Amin et al., [136]
	Modified	Magnetic sewage BC[c]	Not Given	35.50	Biswas et al., [137]

a. BC was modified with suitable precursors (FeSO4.7H2O, FeCl3.6H2O, and NaOH).
b. Hydrothermal reaction was used to prepare the composite.
c. Sewage sludge BC supported alpha-Fe_2O_3 and alpha-FeOOH.

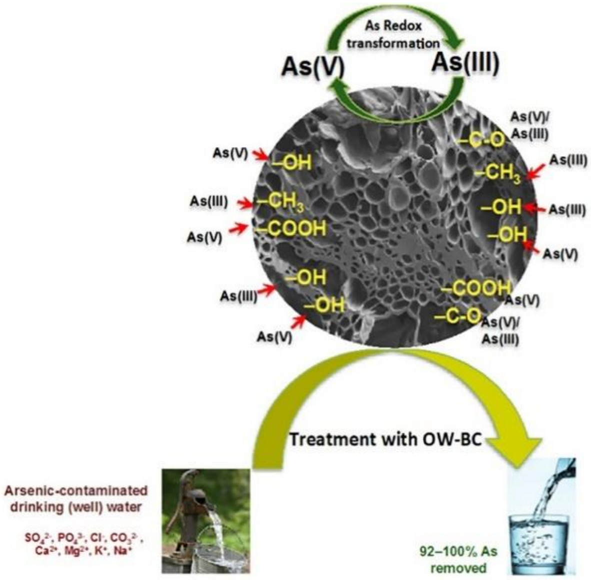

Fig. 2. Sorption of As onto the surface of BC, a general mechanism, adopted from Khan et al., (2018)[120].

In some situations, modifications applied to the structure of BC may have adverse effects on its properties (such as the reduction of SSA), but it can enhance the BC potential for the desired applications. Recent studies have shown that the integration of clay into the structure of BC reduces the available surface area of the BC, which is considered as the main parameter affecting the potential of the pollutants' adsorption capacity of the adsorbents. Recent studies have clearly demonstrated that addition of clay may considerably enhance the potential of the BC to adsorb HM [138] because of the high ion exchange ability of clay-based materials (such as montmorillonite) for various cations. The preparation of magnetic BC composites has gained much attention in recent years as these have proven higher efficiencies compared to non-magnetic BC for the removal of both organic and inorganic pollutants [139]. Magnetic materials represent higher adsorption capabilities, especially for Cd(II), Pb(II), Zn(II), Cu(II), among other HM. Yi et al., [140] reviewed the application of magnetic BC for water treatment to suggest that these materials can considerably enhance the efficiency of BC towards environmental contaminants. According to Tan et al., 2017 [141], the addition of the magnetic compartments (Fe^{2+}/ Fe^{3+}) to the rice straw before the pyrolysis process results in the formation of haematite (γ-Fe_2O_3), and retaining the original OH, COOH, C=O, C=C, and C–O–C functional groups of the biochar, leading to the improvement in the cadmium adsorption. The γ-Fe_2O_3 formed during the pyrolysis process can also contribute to heavy metal adsorption. They also stated that BCs prepared under CO_2 pyrolysis conditions demonstrate higher adsorption capabilities for the heavy metals which can be attributed to the development of oxygen-comprising functional groups such as CO_3^{2-} and PO_4^{3-} under this condition [131,142]. Such groups can for instance adsorb Pb^{2+} [131] through forming pyromorphite (Pyro) [$Pb_5(PO_4)_3X$ (X = Cl, F, OH)] with extremely low solubility [143]. The affinity of CO_2 to react with hydrogenated and oxygenated groups can also lead to a higher specific surface area of BC prepared under carbon dioxide medium, and hence promoting its adsorption capacity for HMs [142]. However, more efforts are needed to achieve a better understanding of the sorption mechanisms involved when incorporating magnetic elements into the BC matrix or under various pyrolysis atmospheres.

Effluents originating from industrial activities are normally laden with various types of environmental contaminants. Hence, one of the main parameters determining the overall efficiency of any treatment technology is the ability to remove a wide range of environmental contaminants. Simultaneous removal of HMs [136–138] has also been reported. A summary of recent findings in this regard is given in Table 4. Research on the production of highly efficient BC with an ability to remove various HM simultaneously from polluted W&W streams, especially from real effluents is currently of high interest in the literature.

Table 4. An overview of BC applications to simultaneously remove HM and the mechanisms involved.

Media	BC type	Target pollutant	Efficiency	Involved mechanisms	Ref.
Wastewater	BC-supported nanoscale zero-valent iron.	Cd(II) and As(III)	148.5 mg/g and 33.81 mg/g within 2 and 1 h for Cd(II) and As(III), respectively.	Adsorption	[126]
Aqueous solutions	Bamboo-based oxidized BC.	Cd(II) and Cr(VI)	0.27 mmol/g and 0.65 mmol/g for Cd(II) and Cr(VI), respectively.	Adsorption	[144]
Aqueous solutions	Titanium-modified ultrasonic BC.	Cadmium and arsenic	72.62 mg/g and 118.06 mg/g for Cd and As, respectively much higher than that of other carbon-materials.	Adsorption	[147]
Polluted water	Sewage sludge-derived BC immobilized nanoscale zero valent iron.	Cr^{6+} and Pb^{2+}	90% and 82% of Cr^{6+} and Pb^{2+}removals, respectively within 30 min.	Adsorption and reduction	[146]
Polluted water	$MnFe_2O_4$-BCnanocomposite	Sb(III) and Cd(II)	237.53 and 181.49 mg/g for Sb(III) and Cd(II), respectively.	Adsorption	[148]
Soil and water	Dairy-manure-derived BC	HMs	The soil samples amended with BC removed groundwater Pb, Zn, and Cd by 97.4%, 53.4%, and 54.5%, respectively.	Adsorption	[149]
Polluted soil	Birnessite-loaded BC in water and soil.	As and Cd	3543, 2412, and 9068 mg/kg for As(III), As(V), and Cd(II), much higher than for the non-loaded BC (no adsorption of As, 4335 mg/kg for Cd).	Adsorption	[145]

Table 5 presents main findings of recent review papers published on the application of BC for the removal of HM from the polluted W&W bodies.

Table. 5. A summary of recently published reviews and highly cited papers published on the application of BC for the removal of HMs from polluted W&Ws.

Subject	Findings/ Remarks	Ref.
General considerations	- There is a need to produce BCs with higher efficiencies towards the adsorption of HMs compared to some activated carbon. This can promote the application of BC for real applications.	[150]
	- Low-temperature production of BC can lead to BCs with high capabilities to adsorb inorganic contaminants. For instance, low-temperature BCs have a greater potential to adsorb As compared with high-temperature BCs.	[151,152]
Mechanisms involved	- Various mechanisms such as physical sorption, complexation, precipitation and electrostatic interactions are involved in the removal of HMs depending on the type of BC and environmental conditions.	[151,153]
	- The Langmuir isotherm and the PSO kinetic model can be used (with the best fit) to describe the sorptive removal of HMs.	[115]
	- Desorption of adsorbed HMs onto BC is currently difficult.	[150]
	- Mechanisms such as surface complexation/precipitation as well as filling the BC pores are dominant for the adsorption of HMs such as As by BCs.	[120,154]
	- Some BCs can represent the potential for multiple contaminants removal (including nutrients, HMs, and organic compounds)	[155]
Knowledge gaps	- The mechanisms in the incorporation of nanomaterials into the structure of BC and the affecting factors need more research efforts.	[140,156]
	- Ecotoxicity of the novel BC based composites (such as nano-BC composites) needs to be investigated deeply in future studies.	[156,157]

3.1.2.3 Organic compounds

Attempts have been made to enhance the efficiency of BC to deal with various types of organic compounds such as dyes, halogenated hydrocarbons, phenolics, pesticides, aromatics, and antibiotics as summarized in Table 6. Both adsorption and degradation are utilized to remove organic pollutants [158,159]. The main focus of these studies has been to investigate adsorption and/or degradation of organic compounds using BC and modified BC.

Adsorption has been the most dominant mechanism involved in the decontamination of W&W polluted with organic compounds. Intermolecular forces such as hydrophobic interaction, H-bonding, dipole-dipole interaction, dipole-induced interaction, π-interaction, coulombic attraction, and covalent bonding are the main mechanisms described for the adsorption of organic compounds by BC [44]. Parameters such as SSA and porosity, ash content, and type of functional groups on the surface of BC determine their adsorption capacity. In general, high pyrolysis temperatures lead to the expansion of micro-porosity and SSA as well as the content of organic carbon and hydrophobicity of BC, which are favourable for immobilization of organic contaminants [150, 151]. For instance, Wathukarage et al., [162] investigated the production of woody tree *Gliricidiasepium* BC under pyrolysis temperatures of 300, 500, and 700°C for the sorption of crystal violet (CV) dye, where the highest adsorption rate was observed for the BC produced at 700°C (at pH=8, 125.5 mg/g). The modified BC also exhibited much higher efficiencies than the pristine BC.

Faheem et al., [163] prepared amino grafted BC (AMBC) with an excellent monolayer adsorption capacity of 89.3 mg/g for an anionic dye. The adsorption of cationic dyes is another possibility of BC application for W&W decontamination. Sewu et al., [164] observed that a Korean cabbage waste BC was highly efficient for crystal violet (cationic) adsorption and not for Congo red (anionic). It was also demonstrated that the ash content and functional groups effectively controlled the adsorption of dyes onto BC. Activation of BC has been demonstrated as an efficient strategy to enhance the efficiency of BC towards adsorption of organic compounds. NaCl [165] and NaOH [166] have been used for the activation of BC to adsorb organic compounds from polluted water bodies.

There are also state-of-the-art reports for the improvement of the specific surface area of BCs by manipulating the pyrolysis conditions. For instance, performing the pyrolysis process under carbon dioxide condition results in the increase on the porosity of the BC due to the tendency of CO_2 to react with hydrogenated and oxygenated groups [142]. Also, there are reports on the post-(thermal)activation of BC under carbon dioxide in order to enhance the specific surface area for the adsorption of organic compounds [167]. In this regard, there is a need for economic and environmental assessments of such technically feasible methods to push them for further commercialization. Doping of the biochar with elements such as nitrogen can also be considered an effective way for promoting the adsorption capacity of BC. This can be due to the increase in the amount of the N-containing functional groups facilitating the adsorption of pollutants. Also, nitrogen doping can promote the π electrons polarization and developing the π-electron-rich sites on the BC surface contributing to the adsorption of contaminants (such as Aromatic compounds [168]. N precursors (especially urea) has also been indicated can act as the activation agent to increase the porosity of the biochar and hence its adsorption capacity [169].

The application of porogens has been also considered as another way to increase the porosity and specific surface area of BC. In this regard, compounds such as $MgCl_2$ have been demonstrated as effective porogens to facilitates the formation of the porous biochar structure due to the increase in the amount of the volatile compounds which are released during dehydration and decomposition of biomass [170]. This method can be considered as a sustainable way to improve the porosity of BC, which can also result in the creation of nanostructured materials in the biochar structure for further catalytic reactions for the decomposition of the adsorbed organic compounds [171].

Despite the benefits of adsorption to remove pollutants from an aqueous phase, the transfer of the adsorbed pollutants to the solid phase causes secondary environmental issues, especially when no efficient desorption methods are applicable. Therefore, development of efficient systems to degrade pollutants [88, 157] have received special attention. In this approach, BC can play a role by acting as a catalyst for the photocatalytic degradation of polluted W&W. The production of BC-based photocatalysts is currently an interesting area of research, especially for BC that perform under visible light irradiation (VLI).

Zhai et al., [173] recently developed a BC@$CoFe_2O_4$/Ag_3PO_4 composite for the photocatalytic degradation of bisphenol A under VLI (λ=420 nm). Other catalytic materials such as TiO_2 (supported on *Salviniamolesta* BC) [174], ZnO [175], and Ag [176] have been applied to BC to deal with organic pollutants. Modified BCs are also suitable to assist in the degradation of organic pollutants via Fenton and Fenton-like reactions [162–164]. For instance, incorpotation of nZVI into the structure of BC resulted in enhancing the efficiency of dyes degradation (100% RY145 dye, 0.5 g/L modified BC) via Fenton reactions [180]. Also, the combination of BC with nZVI was able to promote the electron transfer from nZVI to the pollutant, resulting in its rapid decomposition due to high electrical conductivity [181].

Some oxidation agents have high redox potentials, but need a pre-activation to achieve superior degradation efficiencies for recalcitrant compounds [167, 168]. BC can be efficiently used to activate such agents. For instance, peroxymonosulfate (PMS, redox potential: 1.8 V) was activated [184] by a sludge-derived BC (SBC) for the degradation of triclosan (TCS) from W&W. The SBC having a porous structure (specific surface area = 157 m^2/g) was effective for the activation of PMS towards the target pollutant especially under optimum operating conditions of pH=7.2, BC dosage = 1.0 g/L and PMS concentration = 0.8mM at 25 °C. Regarding the mechanisms involved in the activation of SBC, they concluded that the generation of hydroxyl radicals, sulfate radicals, and singlet oxygen contribute to the degradation of the pollutant. They also discussed that the hydroxyl radicals can be bond to the surface of the biochar promoting the already adsorbed pollutants by the biochar. Regarding the degradation of antibiotics [185,186], Nguyen et al., [187] prepared iron functionalized spent coffee grounds (SCG) BC for the oxidative removal of tetracycline in the presence of persulfate (PS). The authors reported efficient activation of PS, especially under low pH, low initial pollutant concentration, and high PS dosage and BC applied. As mentioned before, the presence of metallic compounds can induce the activation of oxidation agents. For instance, for iron-containing BCs the mechanisms described in Eq. 1 and 2 can play the role of producing the sulfur-based radicals, especially under acidic conditions to decompose the organic compounds. The resulting SO_4^{*-} radicals (Eq. 2) can also react with $S_2O_8^{2-}$ to produce $S_2O_8^{*-}$ which can also contribute in the degradative removal of the organic pollutants (Eq. 3).

$$Fe^{3+} + S_2O_8^{2-} \rightarrow Fe^{2+} + S_2O_8^{*-} \quad \text{(Eq. 1)}$$

$$Fe^{3+} + S_2O_8^{2-} \rightarrow Fe^{3+} + SO_4^{2-} + SO_4^{*-} \quad \text{(Eq. 2)}$$

$$SO_4^{*-} + S_2O_8^{2-} \rightarrow S_2O_8^{*-} + SO_4^{2-} \quad \text{(Eq. 3)}$$

Other mechanisms can be also involved in the activation of PS by BC-based materials. A hydrofluoric acid modified BC was developed [188] to enhance the activation of PS for efficient degradation of acid orange 7 (AO7) in a water solution. They argued that acidic conditions can favor the degradation of organic compounds by the activation of PS. Under acidic pHs, SO_4^{*-} is the predominant radical while under alkaline conditions, it reacts readily with hydroxyl radicals which are of shorter lifetime compared to SO_4^{*-}, resulting in lower degradation efficiencies. Also, Xiangping Li et al., [139] concluded that encapsulated c-Fe_2O_3 nanoparticles promote persulfate activation towards organic contaminants.

BC has also been used for the activation of other sulfate-based chemicals. Specific types of modifications have been so far applied to the structure of BC to make it appropriate for such purposes. Development of BC supported Co_3O_4 composite to activate PMS to enhance the degradation of chloramphenicols (30 mg/L) is an example of the efforts in this regard [189], which has considerably promoted the efficiency of the contaminant degradation compared to the Co_3O_4/PMS system by facilitating electron transfer between Co and HSO_5^-, induced by BC, thus accelerating the Co^{3+}/Co^{2+} redox cycle. Table 6 presents an overview of the efficiencies observed for BC to remove various types of organic pollutants.

Table 6. Highlights of the recent studies performed on the removal of various types of organic compounds by the BC.

Category	Specific Compound	BC type	Findings/ Remarks	Ref.
Dyes	Dye compounds	Various BCs	Efficiencies from 2 to 104 mg/g have been observed for dyes removals by the BCs.	[190]
	Methylene Blue (MB) and crystal violet (CV)	Rice straw eco-friendly (NaCl) activated BC	- The studied dyes were more efficiently adsorbed onto activated BC compared to pristine BC.	[165]
	Anionic Congo Red Dye	Amino grafted BC (AMBC)	- The prepared BC exhibited enhanced monolayer adsorption of the dye due to the presence of both –COOH and –NH_2 protonated groups.	[163]
	Yellow (RY145), red (RR195), and blue (RB19) dyes	Iron oxides and nZVI modified rice husk BC	- The presence of nZVI in the structure of BC considerably promote degradation of dyes.	[180]

	Crystal Violet	Korean cabbage BC	- BC can adsorb crystal violet much higher than activated carbon.	[164]
	MB	TiO_2 supported on medium-density fiberboard (MDF) BC	The removals were 2.3 and 2.2-times faster than those of B5T (5% TiO2) and B1T (1% TiO_2) samples.	[191]
Halocarbons	Chlorinated organic compounds (COCs)	Commercial rice husk-based BC and the laboratory-prepared BCs from corn stalks	Parameters such as high aromaticity and low polarity of BCs and high hydrophobicity of the COCs can promote adsorption of COCs by the BCs.	[192]
Phenolics	Bisphenol A (BPA)	Laccase immobilized magnetic BC	- BPA removal by the BC was attributed to adsorption and enzymatic degradation mechanisms. - The magnetic BC maintained its efficiency over 85% even after seven repeated cycles.	[193]
	BPA	$BC@CoFe_2O_4/Ag_3PO_4$	The photocatalyst exhibited a high degree of efficiency to deal with BPA under VLI even after four cycles.	[173]
Aromatics	Toluene and m-xylene	Municipal solid waste BC.	High efficiencies of 850 and 550 mu g/g for toluene and m-xylene were observed.	[194]
Pesticides	Various pesticides	Various types of BCs	Efficiencies from 0.02 to 23 mg/g have been reported for pesticides removal by the BCs.	[190]
	Atrazine	Iron-modified BC loaded *Acinetobacterlwoffii* DNS32	The magnetic BC was able to efficiently remove the pesticide through adsorption and degradation mechanisms.	[178]
	Various types of pesticides	Various types of BCs	The efficiency of BC towards pesticides can be enhanced through physical (e.g., e-ashing, crushing, sieving), chemical (e.g., magnetizing, and activation), and biological (e.g., composting) modifications.	[160]
Pharmaceutical and personal care products (PPCPs)	Various PPCPs	Various types of BCs	Varying efficiencies (0.001-59 mg/g) have been reported for PPCPs removal by the BCs.	[190]
	Tetracycline	Iron functionalized SCG BC	Modified BC could efficiently activate persulfate for efficient degradation of the pollutant.	[187]
	Fluoroquinolone	Humic acid-coated magnetic BC	Although introducing more humic acid onto the surface of magnetic BC reduced the SSA and porosity of the composite, it could enhance the efficiency of BC towards antibiotic degradation.	[195]
	Solid digestate-derived BC-Cu NP composite	Tetracycline	31.5% and 97.8% of tetracycline degradation were observed using the BC-Cu NP composite (0.5 g/L) in the absence and presence of hydrogen peroxide (H_2O_2, 20 mM), respectively.	[196]
	sulfamethazine (SMT)	Steam activated BC which synthesized from *Sicyosangulatus L.*	The sorption process is highly dependent on pH. The BC exhibited maximum sorption capacity of 37.7 mg/g at pH 3, with 55% higher sorption capacity compared to non-steam activated BC.	[21]

a. Including trichloroethylene, 1,2,4- trichlorobenzene, 1,2-dichlorobenzene , and monochlorobenzene.

As indicated in Table 7, the main mechanisms concerning adsorption and degradation are involved to separate the various types of environmental contaminants from the polluted media.

Table. 7. Summary of the results and conclusions achieved by recently published reviews on the mechanisms involved in the removal of organic pollutants from W&W treatment using BCs.

Subject	**Findings/ Remarks**	**Ref.**
Mechanism(s)	- The mechanisms involved in the adsorption of organic pollutants can be classified as: a) electrostatic attraction, b) H-bonding, c) filling the BC pores, d) π-π electron-donor acceptor interaction, e) complexation, f) hydrophobic interactions, g) partition uncarbonized fraction and h) spectrometer exchange.	[35]
	- BC can induce some advanced oxidation processes in the disinfection of Escherichia coli and degradation of 2-chlorobiphenyl.	[190]

	- Incorporation of γ-Fe_2O_3 nanoparticles can grant catalytic ability to activate oxidation agents such as persulfate.	[139]
	Integration of zero valent iron nanomaterials into the BC structure can induce advanced oxidation processes in parallel to adsorption of the pollutants onto BC/zero valent iron surfaces.	[181]
Effects of the production conditions	- BC prepared under high pyrolysis temperature can provide high surface area and the developed micropore structures in the BCs to favors adsorption of organic contaminants following mechanisms of filling the pores and hydrophobic as well as electrostatic interactions.	[151]
	- BC has shown its ability to deal with a range of organic pollutants including pesticides, pharmaceutical and personal care products, dyes, etc. from the polluted media.	[190]

Among the latest signs of progress in the application of BC for the degradation of organic compounds is the synthesis of biochar-based electrodes for the electrochemical treatment of highly polluted effluents. In such treatment methods, strong hydroxyl radicals (·OH) are generated and contribute to decomposing the organic compounds. Zhang et al., [197] indicated that the addition of elements including Ti, Sn, and Ce can have a significant improvement in the treatment capacity of the BC particle electrodes to deal with coking wastewater. Under optimum operating conditions of 150 min and a current density of 30 mA/m2, 92.91% and 74.66% of chemical oxygen demand (COD) and dissolved organic carbon (DOC) removals were achieved, respectively, by promoting the electrocatalytic degradation reaction. There is also some evidence for the positive effects of the biochar-based electrodes for the improvement of bioelectrochemical systems (BES) such as microbial fuel cells (MFCs). Wang et al., [198] demonstrated that the performance of the MFCs enhanced when the biochar was applied as the anode, due to producing higher power densities compared to conventional carbon felt electrodes (up to 92.0%), resulting in the efficient degradation of AO7 in the simulated wastewater (97%). Huggins et al., [199] discussed that BC-based electrodes are considered as sustainable alternatives for the MFCs electrodes such as activated carbon and graphite granule due to their acceptable performance and the respective environmental benefits as biomass valorization products for carbon sequestration.

3.1.2.4 Multi-contaminants

In addition to studies performed on the removal of specific types of contaminants (i.e., nutrients, HMs and organics), attention has been paid to analyse the efficiency of BC in real applications, where a combination of all or some of the mentioned pollutants can be found [148, 169, 181, [182]. A good example is stormwater runoff, which is one of the sources of clean water recovery and re-use. However, such waters normally contain nutrients such as phosphate and nitrate originating from lawn fertilizers, atmospheric deposits, soil erosion and urban wastes, as well as hydrocarbons, organic compounds and trace metals [202,203].

BC has been successfully applied for the removal of pollutants as described by Ashoori et al., [155] where the potential of BC-amended woodchips was used in a pilot scale experiment for the removal of nitrate, metals and trace organic compounds from urban storm runoffs, suggesting that BC can remove nitrate and Cd, Cu, Ni, and Pb, but it was not capable of removing Zn [24]. Organic compounds can be simultaneously removed together with nutrients [105, 184] and with HM [116, 185]. Table 8 presents an overview of BC application for the simultaneously removal of various types of environmental pollutants and the mechanisms involved.

BC-based electrodes have been also used for the adsorption of multi ions in the water desalination processes. For instance, hierarchical porous carbon (SSA: 1839 m2/g) electrodes fabricated from rice husk biochar [206] exhibited a high electrosorption capacity (8.11 mg/g), reaching the mean deionization rate of 0.92 mg/g/min for 20 mM NaCl. Such a finding can propose a sustainable way for water desalination, especially in the region of the world with limited access to drinking water resources.

3.1.2 Process stability

One of the main drawbacks of most biological treatment methods (such as anaerobic digestion and activated sludge) is their low stability when dealing with non-biodegradable and toxic effluents (such as those from pulp and paper mills [4,5,207]). The presence of recalcitrant and possible toxic components negatively influences the microbial community, leading to failure of the treatment processes. Physicochemical treatment methods have demonstrated a high degree of resistance towards complex and toxic substances. Adsorption capacity of the BC used in the removal of pollutants is directly related to their properties (such as specific surface area including the pore volume) [9]. Besides, BC loses its efficiency with time due to the occupation of the available surface area of the BC with the pollutants. Hence, a precise knowledge about the characteristics of BC-based materials is the key parameter to circumvent the failure or any drop in the system performance. It is vital to assess the performance of BC on real contaminated W&W streams since laboratory scale experiments using a single pollutant are mostly unable to provide adequate information on the BC actual performance.

Table 8. An overview of BC application to simultaneously remove environmental pollutants and the mechanisms involved.

Media	BC type	Target pollutant	Efficiency	Involved mechanisms	Ref.
Wastewater	BC-supported $Mg(OH)_2$/bentonite composite.	Phosphate, ammonium and humic acid	125.36 mg/g for phosphate, 58.20 mg/g for ammonium and 34.57 mg/g for humic acid.	Adsorption (recovery of phosphate, ammonium and humic acid from wastewater)	[204]
Wastewater (Pharmaceutical effluent)	Iron Oxide-BC nanocomposite loaded with Pseudomonas putida.	Calconcarboxylic Acid, NH_4^+ and PO_4^{3-}	Up to 82%, 95%, and 85% for calconcarboxylic acid (CCA) dye, PO_4^{3-}, NH_4^+, respectively.	Adsorption	[110]
Aqueous solutions	BCs from groundnut shells under slow and fast pyrolysis (GB350 and GB700, respectively).	Cd^{2+},$Hg^{2+,}$ and Pb^{2+}	Higher than 99% for Cd^{2+}, and 100% for Cd^{2+} and Pb^{2+} (GB 700). 100% for Pb^{2+} and Hg^{2+} except Cd^{2+} that showed 99.05, 99.46 and 99.69% for Pb^{2+}, Hg^{2+}, and Cd^{2+}, respectively (GB 500). 0.14 mg/g for Hg^{2+} and 0.18 mg/g for Pb^{2+}, and 0.09–0.56 mg/g for binary mixtures, 0.05–0.10 mg/g for ternary mixtures by GB350 and GB700, respectively.	Adsorption	[208]
Polluted water	Modified yak dung BC	Fluoride and arsenic	3.928 mg/g and 2.926 mg/g for F_2 and As(V), respectively.	Adsorption	[209]
Aqueous solutions	BC-supported zero valent iron	Cu^{2+} and bisphenol A	96% and 98% for Cu^{2+} and BPA, respectively	Reduction of Cu^{2+} and the oxidation of BPA (by SO_4^{*-}, as the dominant radical responsible for the degradation of BPA.	[210]
Aqueous solutions	BC-Based Fertilizer	Cadmium	6.3279 mg/g.	Adsorption	[211]
Eutrophic water	Mg-Al-modified BC.	Ammonium, nitrate, and phosphate	0.70 mg/g, 40.63 mg/g, and 74.47 mg/g for NH_4^+, NO_3^-, and $PO^{3-}{}_4$, respectively.	Adsorption	[111]
Polluted water	BC-based and mixed metal oxide catalysts	Toluene (Model Tar), NH_3, and H_2S.	Higher than 95% for the mentioned pollutants.	Adsorption	[212]
Polluted soil	Magnesium-modified BC derived from *Thaliadealbata*	Sediments contaminated with sulfamethoxazole and cadmium	51.4-87.2% for sulfamethoxazole and 56.2-91.3% for Cd.	Adsorption	[213]
Contaminated Soils	Dairy-Manure BC	Lead and atrazine	57% and 66% reduction in Pb and atrazine concentrations, respectively.	Adsorption	[123]
Simulated flue gas	CuO-MnO_x-modified pinecone BC	Formaldehyde and elemental mercury	89% and 83% removals for HCHO and Hg^0, respectively at 175 °C, with 12%CuMn/HBC.	a) Surface adsorption and b) surface oxidation (Hg^0 into HgO, and HCHO into CO_2 and H_2O by the surface active oxygen produced from CuO-MnO_x.	[205]

Ease of the process implementation is another parameter that can potentially influence the stability and reliability of the process. Also, the need for complicated facilities and equipment can make a method less attractive for implementation. When the BC is desired to be used for the treatment of polluted W&W, some steps such as transportation of the BC and possible additives, application of BC and collecting the BC after the treatment process are involved. Among such steps, it seems that the most difficult part is recovering the BC, which can be achieved by filtration. This brings some technical difficulties such as rapid membrane fouling [198, 199] and may bring additional costs for the treatment process. In this regard, new generations of magnetic BC [134, 200] have been developed, which offer the possibility of collecting the utilized BC by applying a magnetic field. However, to the best of our knowledge no commercial W&W treatment facilities have been established yet using such types of BC.

3.1.3 Scale-up capability

The initial step for the scale-up of the technologies which have been already developed in lab-scales is to prove its efficiency to deal with complex conditions such as the presence of multiple pollutants in the content of real effluents [217]. To this end, appropriate optimization methodologies such as the Taguchi experimental approach [202, 203] can be adopted to identify the optimum conditions and maximize the performance of the treatment systems. Even though some reports are available on the application of such optimization methods for BC production processes [204–206], more studies are required for W&W treatment optimization using the already developed BC.

Regarding the large-scale applicability of BC, Vikrant et al., [114] concluded that BC can be considered as an attractive candidate for large scale adsorption of nutrients such as phosphorus from aqueous media. This is attributed to the benefits of BC such as higher efficiency and lower costs compared to conventional adsorbents such as activated carbon and zeolite. In general, the technology has to be competitive with the conventional treatment technologies to encourage investments for scale-up activities. However, there are only limited reports available on the pilot-scale applications of some types of BCs such as BC-nZVI for the stormwater treatment [223]. Pilot-scale studies have been also conducted to assess the efficiency of BC for the removal of multiple pollutants such as nitrate, metals, and trace organic contaminants [224]. For instance, BC-amended woodchips showed acceptable performance under suitable flow control conditions for stormwater treatment [155].

Full-scale production [225] and applications have also been reported to deal with real effluents. Sewu et al., [226] concluded that the superior physicochemical properties of steam-activated BC

(SSA=332 m^2/g, pore volume= 0.29 cm^3/g, and porosity=77.1%) produced from spent mushroom substrate enabled the BC technology for the dye-laden effluent on real scale. Few reports have been published on large scale application of BC in microbial electro-chemical technologies wherein BC served as a simple bioelectrodes [227]. However, it is worth noting that the efforts for full-scale application of BC for the treatment of polluted W&W are limited, especially for those with acceptable performance in lab-scale studies such as magnetic BCs [173].

The possibility of a technology to be combined with other technologies adopted in large-scale to compensate for the weaknesses of both the technologies (at least one of them) can also facilitate the scaling up. In the case of BC, properties such as low cost and high capability to deal with a wide range of pollutants can make it an attractive option for such integrations. To support this, He et al., [113] reviewed the few available studies on the combination of BC with municipal wastewater treatment processes. They concluded that such combinations can be very effective, especially in cold seasons where the concentration of nutrients in effluents is high due to the lower activity of nitrifying and denitrifying bacteria at low-temperature wastewater. Such an approach can also be applied in other wastewater treatment methods such as constructed wetland to improve the overall performance of the treatment [105].

3.1.4 Health and safety risks

Currently, some types of BCs are being produced at large scales and it seems that in the near future, BC-based full-scale W&W treatment plants will be established in many countries all over the world. Sufficient information on the health and safety considerations associated with the production and application of BC is vital to prevent the risks to the workers and to satisfy sustainability aspects.

The routes of human exposure to BC have not been studied well so far. However, dust generated during the BC production and applications can be considered as the predominant route for workplace exposure of persons to BC. For nano-BC [228], the general exposure routes of nanomaterials including dermal, oral, inhalation and ocular [27] also need to be taken into account. The inhalation of BC dust may create some toxic effects in the respiratory tract, but the toxic effects of BC on the exposed organs is not yet well understood or documented. It can be stated that the presence of toxic elements in the structure of BC generally determines the overall toxicity expected from the BC. However, previously it was demonstrated that controlling the BC production conditions can alter the presence and the amount of such toxic elements. For instance, Anyika et al., (2016)[229] studied the concentration of toxic and non-toxic elements in BC as a function of production temperature. They concluded that BCs produced under elevated temperature (650°C) contained less toxic and nontoxic elements and hence, less toxic effects can be expected from the produced BC.

A recent study by Yousaf et al., [230] suggested that pyrolysis temperature is an important determining parameter for stabilizing potential toxic elements in the BC structure. In addition to the pyrolysis temperature, the origin of BC can influence the presence of toxic effects. Devi & Saroha [231] performed a risk analysis to study the toxicity of HMs in BC produced from pulp and paper mill effluent treatment plant sludge containing relatively high HM concentrations to conclude that HM are enriched in the BC after the pyrolysis process. They further stated that higher pyrolysis temperature (at 700°C) decreased the leaching potential of HM. Additional experimental studies on the toxicity of various types of BCs on living organisms were made by Sigmund et al., [232], which is perhaps the first cytotoxic study on BC. The authors concluded that BC produced from the UK BC Research Center's standard BC on NIH 3T3 mouse concluded that BC can have some toxic effects on the fibroblast cells with EC10 values of 49.6 and 18.8 µg/mL after 24 and 48 h of incubation, respectively. The authors advised for the practitioners to wear respiratory protective equipment while producing BC to minimize the risk of exposure. Further, they stated that BCr should be applied in slurries to avoid the formation of dust. In another recent related study, Flesch et al., [233] argued that BCs generated using a Kon-Tiki flame curtain kiln having high quality (certified by the European BC Certificate), but contain high quantities of hazardous materials (e.g., polycyclic aromatic hydrocarbons, polychlorinated dibenzo-p-dioxins and dibenzofurans, polychlorinated biphenyls, and HM), showed no acute toxic effect to ciliates, but high lethal effects to rotifers and cladocerans were observed.

In another study, Yang et al., [234] studied the effects of BC on human liver, lung cell lines (*in vitro*) and on *Drosophila melanogaster* (fruit fly) (*in vivo*) to conclude that BC had negligible impact in the viability of flies, but it could inhibit the growth of the cells. However, it is evident that studies performed so far are not sufficient to have a scientific-based conclusion on the toxic nature of BC and its effects on the human body. It is especially of high importance for those types of BC that have proven their applicability in terms of efficiency and economic considerations. For instance, magnetic BC are currently attracting attention for the treatment of polluted W&W. However, to the best of our knowledge, toxic behaviour of magnetic BC is not well studied and documented. That means better understanding about toxicity and to produce less toxic materials can lead to the wider application of magnetic BC for real large-scale applications.

There are also state-of-the-art findings in the literature revealing the possibility of the presence of highly metal cyanides such as KCN or NaCN in cyanide ion (CN^-) biochar. Luo et al., [235] discussed that oxygen-containing alkali metal salts (e.g., K_2CO_3) can promote the N-rearrangement reactions which result in the generation of substances such as KOCN which can be further reduced to highly toxic KCN [236] in a carbon-rich matrix. They also proposed to add metal chloride salts such as $FeCl_3$ and $MgCl_2$ to hinder the N-rearrangement reactions due to their high binding energies. In this regard, there is a need for such in-depth studies to identify the possible toxic compounds in the content of BCs from various feedstock materials, and to develop the methods to eliminate them before using the BCs for real applications.

3.2 Environmental fate

In spite of the potential benefits of BC for environmental applications (i.e., treatment of polluted W&W) and for carbon sequestration [218, 219], some concerns have been raised on the environmental consequences of BC production and the behaviour and fate of the produced BC when introduced in the environment. The pyrolysis process can indeed result in the release of air pollutants (CO_2, NO_x, and particulate matter) to the atmosphere. For instance, Yang et al., [239] calculated the greenhouse gas emission intensity from a typical fixed-bed pyrolysis process in China to be 1.55E-02 kg CO_2-eq/MJ. From the already performed life-cycle assessment (LCA) studies, it can also be stated that the cultivation can be considered as the main contributor in the biochar-based technologies life cycle, followed by pyrolysis and transportation (e.g., 93.0, 23.3, and 4.8 kg CO_2 eq/t, respectively, for the production of Miscanthus [240]). There is also some evidence emphasizing the impact of the feedstock materials on the extent of the environmental impacts from the biochar production. For instance, it has been demonstrated that the production of BC from willow is preferred compared to from pig manure from an environmental point of view [241]. This is mainly due to the necessity of feedstock drying when pig manure is used as the raw material.

Recently, methods have been developed to reduce such emissions, e.g., the NO_x emission from the pyrolysis of ferric sludge [242], suggesting that the presence of iron in the feedstock could fix nitrogen preventing its emission to the atmosphere. The BC production conditions also influence the atmospheric emissions. Dunnigan et al., [243] demonstrated that higher rice husk pyrolysis temperatures may increase the bio-oil production as well as PM_{10} and $PM_{2.5}$. Also, generating electrical power for the pyrolysis may be responsible for greenhouse gas emissions, especially when applying non-renewable and fossil fuels.

In order to mitigate the atmospheric emission of pyrolysis processes, part of the produced BC can be used to remove the produced air pollutants as has been recently emphasized [223, 224]. A simultaneous adsorption of NO and CO_2 onto BC has been studied by Zhang et al., [246], but more additional studies are required to investigate the effectiveness of BC for these applications. Novel techniques have been introduced recently to apply clean sources of electricity production from renewable sources such as solar energy. For instance, concentrated solar power systems (CSPS) [225–227] can considerably contribute to the reduction of greenhouse gas emissions. A CSPS was utilized to provide the required energy for the pyrolysis process from date palm. The study showed that CO_2 emissions from CSPS-based pyrolysis account for only 38% compared to conventional pyrolysis processes.

During the production of BC, some contaminants such as polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), heavy metal particles and carbon nanoparticles are generated that can remain in the BC. The release of such compounds after BC application may create a threat to the receiving environment. This aspect has been covered in a study on the fate of BC after being used for soil treatment applications as discussed by Lian & Xing, [250] (see the illustration in Fig. 3). The authors further studied BC transport in the environment. Phenomena such as decomposition, runoff and infiltration are involved in the transportation of the BC depending on the environmental conditions. Gonc et al., [251] demonstrated that BC addition can bring some positive effects to the receiving environment such as accelerating the degradation of complex compounds such as polyhydroxybutyrate-co-valerate (in a tropical soil system). The authors also argued that the effects can be correlated with the improvement of soil microbial community, which would promote the degradation of compounds that BC might have released into water bodies. In such situation, BC might have adsorbed various compounds (HMs and organic compounds), leading to a reduction of bioavailability of such compounds in the media. In addition, BC may participate in processes such as advanced oxidation processes involved in the decomposition of organic compounds, especially under the solar irradiation conditions.

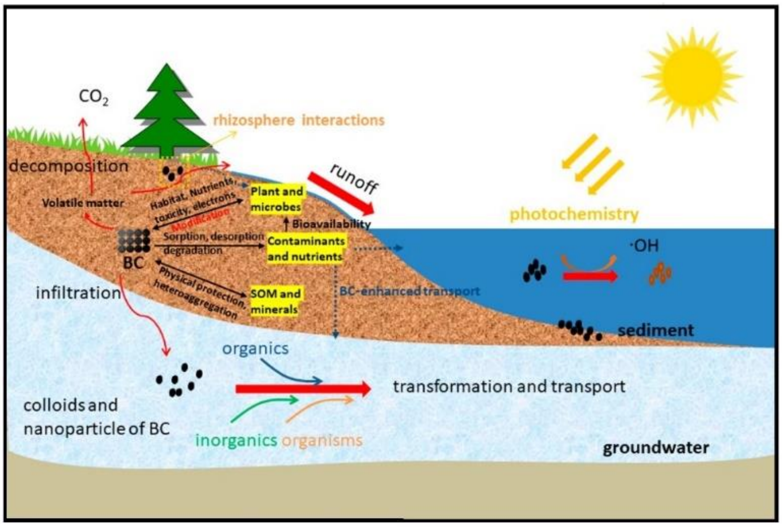

Fig. 3. The fate of BC in the environment, adopted from Lian & Xing, (2017)[250].

Dissolution is another factor responsible for the release of elements from BC into the receiving environment. Limwikran et al., [252] stated that elements such as K (up to 64%), Ca (up to 40%), and P (up to 75%) can readily be released from the BC matrix to water bodies. Considering the fact that relatively high amounts of BC are required to be used in W&W treatment, dissolution and release relatively high concentrations of some of toxic pollutants into the environment. Aller [253] reviewed the fate of various types of BC to conclude that the application of BC with high loads of contaminants should be avoided to prevent subsequent environmental issues. In this regard, there is a need for specific standards for the potentially toxic elements in BC for certain applications such as the treatment of polluted W&W.

With regard to the ecotoxicological effects of BC, Table 9 summarizes the results of various studies performed to realize that the majority of the standard methods developed so far considered ecotoxicological effects of BC on soil invertebrates and plants. BC is certainly expected to remain in the receiving environments for a long time and if the used BC is released into the soil environment, it may remain there for hundreds or even thousands of years. Therefore, the effects of "aged" BC on the environment will have high priority as some reports are already available exploring the long-term effects of BC in the soil. For instance, Yao et al., [254] indicated that aged BC could influence the physicochemical properties of black soils, including pH, carbon, phosphorous and nitrogen contents, NO_3-N, C/N ratio, and soil bulk density in the northern parts of China even after three years after the amendment. It is, therefore, worthy to mention the urgent need for further studies on the fate of BC and its effects on environmental parameters. Such a study has a high priority, particularly to investigate the influence of BC production conditions (e.g., pyrolysis temperature) on the ecotoxicological behaviour of BC. However, in the absence of such detailed information, some measures can be adopted to control the probable environmental and ecotoxicological impacts of BC. Development of magnetic BC, which would allow the separation and collection of the used BC can be considered as an effective way to prevent the discharge of BC into the environment.

Table 9. A summary of the achieved results of BC ecotoxicological effects.

BC type	Studied organism/ toxicity indicator	Remarks	Ref.
Sewage sludge BC	*Enchytraeuscrypticus*/ the predicted no-effect concentration (PNEC)	- The studied sewage sludge BC contained relatively high amounts of Cu, Zn, and Pb. - No toxic effects on were observed under BC (<4.8 t/ha).	[255]
BC-based organic N-fertilizer	- *Eiseniaandrei* (epigeic earthworm/ weight and vertical distribution - Germination and growth of *Brassica rapa* (turnip)	- Small-scale Terrestrial Ecosystem Models (STEMs) were used for this study. - No toxic effects on the studied earthworm were observed after 28 days exposure in the STEMs. - BC addition at 25 t/ha considerably decreased the plant germination and no germination at 75 and 100 t/ha.	[256]
Biogas production residues BC	*Folsomia candida* and*Lepidiumsativum*/ growth	- The produced BCs fulfilled the recommendation about heavy metals and PAH contents. - Pyrolysis temperature and the feedstock condition had significant impacts on the BC toxic effects on springtails. - BC from the separated feedstock, prepared under temperature lower than 800°C demonstrated low toxic effects to the tested microorganism.	[257]
Vegetable waste, pine cone and their mixture (1:1 by weight)	Human liver and lung cell lines and also on *Drosophila melanogaster* (fruit fly)/ viability and growth	- BC had negligible impact to the viability of flies - BC could inhibit the growth of the cells.	[234]
Wood-derived BC and coconut shell-derived activated carbon	*Meretrixmeretrix*(a marine clam)/ The growth and nutritional quality	- The studied materials had no effect on the sediment pH and its calcium content. - The materials significantly increased the electrical conductivity (EC) and total organic carbon (TOC), but decreased the dissolved organic carbon (DOC). - BC inhibited clam shell growth and had no effect on the soft tissue growth. - Activated carbon had no significant effect on the shell growth, but decreased the soft tissue weight.	[258]

Environmental LCA of biochar-based systems have indicated that carbon sequestration, and fossil fuel substitution are the main contributors in the climate mitigation potential [259–261] when such systems are utilized in various applications. For instance, according to the results of a recent study, biochar-amended manure composting resulted in a great global warming potential (GWP) mitigation potential [262]. However, such LCA studies for water treatment applications are rare in the literature. Huang et al.,[263] demonstrated that the sewage sludge biochar prepared using microwave (300 W) with high iron content in heterogeneous Fenton Oxidation of trichloroethylene (TCE) has no significant impact on the ecosystem. The concentrations of heavy metals (i.e., chromium, copper, nickel, lead, and zinc) found in the leachate generated from biochar were lower than the standards for non-drinking water use.

3.3 Economic considerations

Economic considerations are of high priority for commercializing the technologies developed on laboratory scale, wherein raw material price and the applied technologies for BC production are important. Ahmed et al., [264] studied the overall costs of BC production and its applications in W&W treatment. The cost associated with the production of BC is considered as one of the main bottlenecks, which can potentially prevent its rapid commercialization for the real applications [265]. There are also limited number of life cycle costs and economic analysis of biochar-based technologies. Homagain et al., [266] suggested that the annual pyrolysis cost of a 1 MWh plant is around $381000 as the most expensive stage for BC production. Sorensen and Lamb [267] estimated the actual cost of purchasing and transporting red oak (*Quercusrubra*) BC for large scale application to about 290 $/ton. Shackley et al., [268] provided a range of 222 to 584 $/ton for BC produced in the UK, depending on the feedstock used and complexity of the pyrolysis process. In another study, Maroušek, [269] provided a rough cost estimation of 500 $/ton for pristine BC, while Rosales et al., [270] suggested that costs of BC production is around 0.076 $/kg, which is about 3-6% of the price of other commercial carbonaceous adsorbents. Thus, it seems that recent progress in BC production technologies has considerably reduced the BC production costs to make them attractive candidates for applications in the treatment of polluted W&W.

Attempts have also been made to introduce more economic strategies for the production of BC. For instance, Zhou et al., [271] developed a low cost *in situ* technique, called burning and soil covering (B-SC) to be performed by farmers on crop production residues. The BC production cost also depends on the energy price as was stated by Pratt and Moran [272] as they emphasized that the price of electricity in North America is much higher than in Europe. The very low electricity price in some countries (such as in the Middle-East) may provide favourable conditions for BC production and application. In this regard, and with the aim of reducing the production costs, some novel technologies have been recently developed and applied. One such example is solar energy. Giwa et al., [273] performed the pyrolysis of date palm waste using a concentrated solar thermal energy facility to conclude this is an economically viable technology compared to the conventional methods developed for BC production, with a payback time of 4 years and 132 days. Also, they estimated an internal rate of return of 14.8% and a return on investment of 22.9%.

Recent studies have indicated that pristine BC are not efficient enough to deal with environmental contaminants [114]. Hence, some modifications on surface functionalization were required to promote the efficiency for the intended applications. As stated before, various modification methods, each requiring the use of certain precursors, equipment and experts are to be allocated as part of the financial resources. The incorporation of metallic compounds has also been demonstrated to be an efficient technique to improve the properties of BC towards environmental contaminant removal. Various metallic compounds have been used recently for this purpose. The Mg-impregnated BC with a relatively low production cost of 1.2 US dollars/ton by Chen et al., [102] showed a high efficiency (89.25%) for phosphorus removal. A very low cost for the functionalized BC satisfied the sustainability considerations of BC [28]. Several authors have attempted to provide an estimation of the overall operating costs of BC for the treatment of polluted W&W. Chicken manure amine-modified BC was used to adsorb dimethyl sulphide from the aqueous solution with an adsorption capacity of 1.14 (mg/g) and a production cost of 1.60 \$/kg including transportation, chemicals and electrical energy.

Detailed studies emphasizing the cost-effectiveness of BC produced for the treatment of polluted W&W provided exact cost estimations [248–250]. As such, including the involved BC production and operating costs, which opens opportunities for decision makers to compare various BC-based technologies and to aid adopting the most sustainable W&W treatment technologies among the existing alternatives? It is of high importance for some novel types of BC such as those impregnated with magnetic particles [277].

In conclusion, this review demonstrates that BC can be considered as a cheap and cost-effective solution to deal with the polluted W&W when compared to other novel and conventional technologies. Earlier, Kamali et al., [27] discussed the sustainability considerations involved in the application of engineered nanomaterials for the treatment of contaminated W&W to conclude that under the present situations, the production costs of 0.03-1.21 \$/g for TiO_2 nanoparticles, and 0.05-0.10 \$/g for nano zero valent iron particles may be expected to be relatively high compared to those of the reported BC.

3.4 Social considerations

Social acceptability is also among the most important sustainability criteria, which can promote the wider application of BC-based materials for the treatment of polluted W&W. However, some variables need to be considered to determine the social acceptability of a newer technology. Odour and noise impacts as well as the potential to create new job opportunities are among the most important parameters, which will certainly influence the social image of any developed technology [278]. Compared to other technologies such as biological treatment methods (especially the activated sludge process) [253, 254], no odour problem can be expected from the application of BC for the treatment of polluted W&W. Like most of the chemical methods for W&W treatment, the level of noise created by the application of BC can be considered negligible. Development of BC-based W&W treatment technologies can recruit experts in the field. Other professions may be required, directly or indirectly, to operate the BC production facilities to transport the required chemicals and the produced BC along with the treatment processes. Such large-scale activities may engage the local, regional, national or even international markets for trading services, equipment, materials and products, which may lead to the creation of new job opportunities. However, variables such as technology attributes and dimensions, and the required supplementary technologies can determine the exact number of job opportunities that can be offered by the commercialization of novel technologies [47, 255]. Regarding the overall image of the technology, very few studies have been performed on the BC application at large scale, which can potentially support much wider applications of BC [282]. More additional studies are required to demonstrate the social acceptance of BC application in various scientific areas, especially compared to other developed or under developed technologies [283].

4. Conclusions and future research directions

Various biological and physicochemical technologies have been invented recently and applied for the treatment of polluted W&W. The BC-oriented technologies have been developing rapidly, but mainly in the lab and at small scale, and a limited number of developed technologies has been transferred from laboratory scale to large scale applications. Various parameters are responsible for the slow commercialization. In this study, the progress in this field has been assessed including technical, environmental, economic and social considerations. As per the results achieved, some types of BC such as magnetic granted generations, which are assumed to be efficient enough and economically beneficial (by providing the possibility of recovery and re-use) have the highest potential for rapid commercialization. However, more studies are required to provide the opportunities for the decision makers to select the most sustainable alternatives among the existing BC-based W&W treatment technologies. Table 10 provides some useful recommendations for future studies, and based on the results discussed in the present review, the versatile area of BC application needs to be promoted for the real W&W applications.

Table 10. Recommendations for future studies on the application of BCs for W&W treatments (based on the sustainability criteria).

Associated sustainability pillar	**Remarks**	**Related Literature**
Technical (Production processes)	To satisfy the sustainability of BC production, some measures such as the possibility of continuous production, to improve the energy performance of the system, optimization of BC production processes using efficient optimization methods such as Taguchi experimental design to increase the BC yield, bi- and co-products recovery and the application of available and cheap feedstock can lead the BCs with enhanced properties should be considered for further studies.	[219,284–286]
	Co-pyrolysis (such as lignocellulosic and macroalgae biomasses), which can be used to improve the overall performance of BC in terms of technical and economic considerations should be studied with more details including the economic considerations.	[287]
	Wood-based BCs can be used as an effective (compared to the non-woody materials), simple, cost- effective and environmentally friendly material to deal with environmental contaminants in the context of drinking water and wastewater, especially in developing countries. In this regard, more comparative studies as well as the detailed economic analysis are recommended for future studies.	[288]
	Pyrolysis temperature can determine the BC properties such as mainly morphology and surface properties, elemental composition, conductivity, redox potential as well as pH, CEC, and VOCs. The effects of pyrolysis temperature on the properties of BC such as stability (the potential for the release of materials) as well as cost-effective analysis are some directions for future studies.	[289]
Technical (Efficiency)	- Integration of clay into the BC structure (clay-BC composites) can potentially enhance its adsorption potential towards the pollutants despite the decrease in surface area of the BC by the blockage of BC pores with the clay particles. In this regard, application of other clay-based materials such as bentonite and performing the comparative studies can be recommended. Also, the efficient methods such as ultrasonic irradiation in order to enhance the porosity and surface area of such composites are highly recommended.	[138,290–293]
	According to the techno-economic analysis performed, functionalized BCs are technically and economically applicable to remove a wide range of environmental contaminants such as dyes. More studies are required to prove the efficiencies of such BC-based materials including the detailed cost-benefit analysis.	[294, 295]
	- Modification in the properties of BC can make them appropriate to remove/degrade a wide range of environmental contaminants simultaneously. It can enhance the overall treatment efficiency. In this regard, more studies are required to demonstrate the ability of BC for simultaneous removal/degradation of various organic and inorganic compounds. - The potential of BC to deal with various contaminants simultaneously can diminish the need for complementary treatments and hence, to reduce the overall treatment costs. In this regard, more studies are required to increase the efficiency of the lab developed materials to deal with the real waters and wastewaters polluted with various organic and inorganic pollutants.	[147,194,204,296–298]
Technical (Applicability)	Due to the considerable reduction in the BC production cost, comparative studies are highly recommended in order to control the cost-effectiveness of BC compared to other physico-chemical and biological methods developed so far for the treatment of polluted waters and wastewaters.	[299,300]
Economic/environmental (Recovery and reuse potential)	Incorporation of BC with magnetic materials may grant the capability of being recovered and recycled after being used for the treatment purposes. More studies are required to explore ecotoxicological and environmental consequences of such novel materials. Economic analyses are also required to indicate the cost-effectiveness of such novel materials.	[139,140,216,301]
Environmental (GHSs mitigation)	BC has proved a high potential for greenhouse gases mitigation in many regions of the world such as China (e.g., - 0.94 t CO_2 equivalent (CO_{2e}) per ton of straw). However, more studies are required to trace the fate and environmental impacts of BCs.	[302–304]
Environmental (BC characteristics)	The BC production conditions can influence the presence of some environmental contaminants such as polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs). In this regard, there is a need for standardized procedures for quantitative analysis of PAHs and VOCs in the structure of BC, especially under environmentally relevant conditions.	[305]
Economics (Initial investments)	Selection of the most suitable sites for BC production process facilities can reduce the BC prices by entering the criteria such as land price, access to the required surrounding facilities and resources, etc.). More studies are required for the selection of the most suitable sites for the establishment of BC production facilities.	[306]

Economic (Processing and production cost)	Renewable sources of energy (such as concentrating solar power technologies) can be efficiently and economically combined with the pyrolysis process to produce BC and to reduce the operating costs. More studies are needed to remove the existing technical barriers.	[273,307]
	- There are some evidence for the positive net value [277] of the BC production. However, more studies are required to investigate the economic parameters of BC production and application of the treatment of polluted waters and wastewaters.	[302, 308,309]
Economic (Operating costs)	- Some pieces of evidences are available for lower cost of treatment of environmental contaminates, especially HMs compared to other technologies such as activated carbon. There is a need for more comparative studies in this regard. For the success in the BC application and its rapid commercialization for real applications, reduction of BC price is inevitable.	[303,310]
	- Public financial incentives (e.g., BC in carbon credit systems) can promote the commercialization of BC for various applications. More investigations are required to support this idea.	[311,312]
Social (Social acceptance)	- Few social studies have shown that the application of BC can be socially acceptable. However more studies are required to have a comprehensive conclusion on this subject.	[282,313]

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