Biological Treatment for Biochar Modification: Opportunities, Limitations, and Advantages

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Abstract Biochar is a prominent adsorbent for environmental remediation. The physicochemical properties responsible for adsorption can be significantly enhanced by using physical, chemical, and biological treatments of biochar. The biological treatment methods are advantageous in terms of cost-effectiveness and reduced secondary pollutants. The present chapter summarizes the need, methodology, modification mechanism of biological modification of biochar, and its implementation for environmental remediation. The biologically modified biochar can be obtained by either ex situ (pyrolysis of anaerobically digested residue) or in situ (using extracellular enzymes) technologies. The process includes colonization and biofilm formation by microorganisms on biochar surface and attachment of microbes. Biologically modified biochar metabolizes organic/inorganic contaminants and helps in adsorption, biodegradation, and bio-adsorption simultaneously.

1 Introduction

Generally, the pristine biochar has less adsorption capacity for the removal of contaminants as compared to modified biochar. Different modification methods are developed to increase the adsorption capacity of biochar for its utilization in soil remediation, energy storage, and wastewater remediation. These practices for the production of engineered or modified biochar are termed as biochar engineering (Ok et al. 2015). So, engineered/modified biochar can also be defined as a derivative of biochar with improved specific surface area, porosity, cation exchange capacity, and surface functional groups through biological, physical, chemical, or combination of these methods. The improved physicochemical properties provide significantly better adsorption capacity of modified biochar as compared to pristine biochar (Rajapaksha et al. 2016; Yao et al. 2013a, b, c).

Biological modification using earthworms is emerging as a potential method of biochar modification for increment in surface area, better pore size distribution,

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surface functional groups, and adsorption capacity for heavy metal contamination in soil. The enzymes generated by gut epithelium of earthworm and other symbionts are catalase, b-Deglucuronidase, alkaline phosphatase, d-aminolevulinate dehydratase, and superoxide dismutase. The biochar particles bind with these enzymes through mucus. So, this process can be employed where earthworms can ingest the substrate and discharge the enzyme coated modified biochar. This biologically modified biochar consists of enormous exo-enzymes (molecular ligands). The ex situ modification can be performed by activation of waste/sludge obtained as cow dung, leaf litter, anaerobically digested biomass, etc. This chapter explains in detail the methodology, mechanism, applications, and need for biological modification of biochar through metabolic enzymes.

2 Biological Modification Techniques

The metabolic pathways possessed by microorganisms, viz. Aeromonas, Cellulosimicrobium, Chloroflexi, Shewanella, Streptomyces, etc. (Mohammadipanah and Dehhaghi 2017; Wink et al. 2017), enable the biochar to integrate with various organic compounds and result in usable metabolites (Dehhaghi et al. 2019a, b) and value-added products (Dehhaghi et al. 2018, 2020; Sajedi et al. 2018). Due to their microscopic size, they can penetrate into pores of biochar and develop a non-washable rigid structure of biofilm. The biological modification process includes colonization and biofilm formation by microorganisms on biochar surface. The general mechanism of pollutant removal by biologically modified biochar is illustrated in Fig. 1. Initially, microbes get attached to biochar surface through sticky extracellular polymers and the

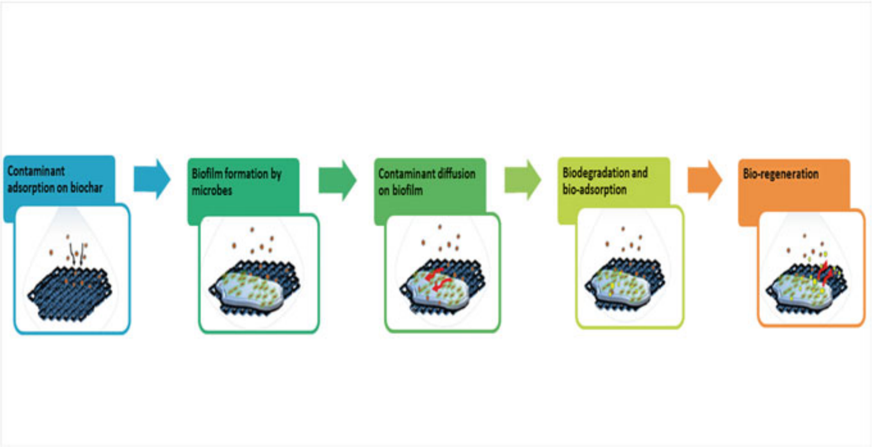

Fig. 1 Bio-adsorption, biodegradation, and adsorption on biologically modified biochar

contaminants get attached to it through molecular diffusion. These organic and inorganic pollutants get metabolized by microbes through various bio-electrochemical and biochemical reactions (Sharma et al. 2020). The biofilms perform degradation and removal of various inorganic, organic, and biological pollutant (Simpsosn 2008; Bouabidi et al. 2019; Sharma et al. 2020). A biologically modified biochar performs pollutant remediation in several steps, viz biofilm formation followed by biodegradation, desorption, and diffusion of contaminants at biochar–biofilm and air/soil/water interface (Wurzer et al. 2019).

Biological treatment enhances the desired physicochemical and functional properties of biochar. It enables the simultaneous adsorption of contaminants on biochar scaffold and their degradation by inoculated microorganisms. For example, several microorganisms (viz. Clostridium, Paenibacillus, Aeromonas, Cellulosimicrobium, Chloroflexi, Shewanella, etc.) possess bio-adsorbent characteristics for heavy metals (Hamedi et al. 2015; Mohammadipanah et al. 2015). The microbial colonization on biochar facilitates the adsorption of inorganic contaminants (heavy metals) with removal and degradation of organic contaminants (naphthenic acid) simultaneously (Frankel et al. 2016). It was observed that the biochar-active biofilm can efficiently perform adsorption and degradation (about 98% of carbamazepine) as compared to conventional sand-active biofilm (about 7% of carbamazepine) in a sewage treatment plant. The caffeine, ranitidine, and metoprolol adsorption characteristics were found similar for both conventional and biochar-based scaffolds (Dalahmeh et al. 2018).

2.1 Interaction of Biochar with Intestinal Enzymes of Earthworms

Earthworms can significantly change the physicochemical and biological properties of consumed substrates (Jones et al. 1994; Yuvaraj et al. 2019). The gut of earthworm/manure worm has various anaerobic (Clostridium, Paenibacillus, Aeromonas, Cellulosimicrobium, Chloroflexi, Shewanella, and Streptomyces) and aerobic (Photobacterium, Pseudomonas, and Bacillus) bacteria that releases many enzymes (Hong et al. 2011). The gut of *Perionyx millardi, Drawida willsi, Drawida calebi, Dichogaster bolaui,* and *Pontoscolex corethrurus* type of earthworms have sufficient quantity of phosphatase, lipase, urease, amylase, chitinase, protease, and cellulose enzymes (Parle 1963; Mishra and Dash 1980; Baskaran et al. 1986; Mishra 1993). The anterior portion of earthworms have higher enzyme secretion as compared to the posterior portion. It is due to that fact that fore-gut and stomach of earthworms have the enzyme secreting parts (Tillinghast and MacDonnell 1973). Mishra and Dash (1980) and Nakajima et al. (2003) have asserted that the cellulase, amylase, protease, and lipase are the most secreted enzymes from intestinal cells of earthworms. Urbasek and Pizl (1991) have stated that the mid-gut of *Lumbricus terrestris* earthworm releases 20 enzymes from three different sections, namely typhlosole, peripheral intestinal epithelium, and peripheral chloragocytes. More than

44% of enzymes (such as b-Deglucuronidase, superoxide dismutase, catalase, d-aminolevulinate dehydratase, and alkaline phosphatase) are produced in peripheral chloragogen. Also, the maximum proportion (about 70%) of glutamate dehydrogenase, isocitrate dehydrogenase, NADH, and NADPH diaphorase was also found in the mid-gut of earthworm. Similar to a tubular reactor, the gut also maintains the optimum temperature to avoid enzyme inactivation. During vermicomposting, the urease, dehydrogenase, acid, and alkali phosphatases catalytic activity increases initially and thereafter decreases as optimum concentration is reached. This phenomenon specifies earthworms as bioreactors for organic waste with microorganisms (Balachandar et al. 2020; Karmegam et al. 2019).

The interaction with earthworm enzymes can be a potential mode for biochar surface modification. An enormous quantity of organic waste can be ingested by earthworms and also an abundant amount of metal ions can get accumulated in chloragogen tissues of earthworms (Yuvaraj et al. 2020). The implementation of biochar with earthworms can significantly minimize the heavy metal concentration in soils (Shaaban et al. 2018; Sun et al. 2016). The abiotic components in biochar can enrich the soil with minerals and earthworms can induce the degradation process. The biochar particles bind with gut enzymes through mucus of earthworms (Urbasek and Pizl 1991). The mucus ejected from gastrointestinal epithelial cells consists of amino acids, mucopolysaccharides, and glycoproteins (Zhang et al. 2016a, b). The other enzyme originated from earthworm gut such as alkaline phosphatase, amylase, nitrate reductase, cellulose, and acid phosphatase can induce microbial growth. Therefore, the intestines of earthworms and symbionts can be seen as potential sources of extracellular enzymes for biochar activation.

The co-application of biochar with earthworms was found to contribute significantly to soil nutrient enrichment (Ameloot et al. 2013; Puga et al. 2015). During vermicomposting, the ingested biochar by earthworms interacts with intestinal enzymes and is discharged with humus-like substances (Domene 2016). Sanchez-Hernandez (2018) have experimented with *Aporrectodea caliginosa* and *Lumbricus terrestris* earthworms in biochar mixed soil and harvested b-glucosidase, alkaline phosphatase, and carboxylesterase enzyme coated biochar released by earthworms. In another experiment, Sanchez-Hernandez et al. (2019) mixed 2.5–5% (w/w) biochar with soil and interacted with *Lumbricus terrestris* earthworms, and obtained enzyme coated biochar on the top of soil surface. The carboxylesterases induce biological modification/activation of biochar and can effectively remediate organophosphorus-contaminated soils. It can be explained by binding of carboxylesterases with oxygen analogs of organophosphorus (Wheelock et al. 2008).

2.2 *Pyrolysis of Anaerobically Digested (AD) Waste*

Apart from microorganism incubation, the biologically modified biochar can also be produced from the residues obtained after anaerobic digestion (AD) of biomass. The biochar produced from AD residue possesses a higher specific surface area, anion exchange capacity (AEC), cation exchange capacity (CEC), hydrophobicity, alkaline pH, and more negative surface charge as compared to conventional biochar (Yao et al. 2018). These variations in properties might be attributed to the alteration of redox potential and pH values of biomass during anaerobic digestion (Inyang et al. 2010). The enhanced AEC and CEC facilitate the utilization of biologically modified biochar for sequestration of both positive and negative ions from water. The higher cation adsorption capacity of AD biochar is due to the strong negative surface functional groups and negative zeta potential. The presence of strongly negative surface functional groups in modified biochar (due to negative zeta potential of AD waste) increases the cation adsorption capacity. The emerging industrial applications of modified biochar enhance the economic and environmental feasibility of biochar production from AD residue (Dehhaghi et al. 2019b; Tabatabaei et al. 2019). Another biological approach for biochar modification includes the utilization of mineral enriched biomass through bioaccumulation for the production of modified biochar (Yao et al. 2013b; Wang et al. 2017). This process results in value-added biochar nanocomposites and provides a safe disposal method for hyper-accumulating plants. Several studies on biochar production from bagasse stillage waste sugar beet residue, dairy waste, animal waste, and sewage sludge digested slurry were performed at different pyrolysis temperatures (300–1000 °C) under an inert atmosphere (Ma et al. 2018; Inyang et al. 2012; Yao et al. 2011, 2015, 2017a, b). Another study by Inyang et al. (2010) reported the comparative analysis of biochar produced from sugarcane bagasse and AD bagasse. These studies imply that the BET surface area of biochar produced from digested biomass was slightly higher than that produced from biomass pyrolysis. It facilitates the efficient utilization of modified biochar as a low-cost adsorbent for soil amendment, water holding capacity, and soil quality improvement that leads to sequestration of atmospheric carbon. It was concluded that the organic functional groups present in biochar and AD biochar were mainly hydroxyl, alkene, and aromatic groups. The major difference in organic groups was evident only as the presence of carbonyl groups in AD biochar (Inyang et al. 2010). Based on the physicochemical characterization, it is evident that AD biochar has higher adsorption and ion-exchange capacity relative to undigested biomass residues. Scanning electron microscopy (SEM) of AD biochar indicated the presence of several prismatic, hexagonal crystalline structures, and the pore diameter was found similar to the wood-based activated carbon (Ma et al. 2018; Gundogdu et al. 2013; Inyang et al. 2012). Studies indicate the significant effect of different AD biomass on the physicochemical properties of AD biochar. The AD biochar also possesses good heavy metal adsorption capacity from aqueous solutions. The results concluded that the animal waste AD biochar acquire a stronger affinity to Pb^{2+} (99%), Cu^{2+} (98%), and weaker affinity to Cd^{2+} (57%), Ni^{2+} (26%) as compared to sugar beet residue AD biochar (Inyang et al. 2012). Batch experiments of soil remediation indicated that the pH and coexisting anions in initial solution can significantly affect the phosphate adsorption capacity of AD biochar (Yao et al. 2011). The comparative analysis of biochar, anaerobically digested biochar (DBC), and commercially activated carbon (AC) asserted that DBC is the most efficient lead adsorbent in aqueous solutions. The lead adsorption capacity of DBC (653.9 mmol/kg) was twice of AC (395.3 mmol/kg) and several times greater than that of BC (31.3 mmol/kg). Despite lower surface area of DBC, the lead adsorption capacity of DBC was observed higher than AC and BC. This phenomenon suggests the involvement of other mechanisms along with surface adsorption. Post-adsorption analysis using X-ray diffraction (XRD) and SEM identified lead minerals on the DBC surface as cerrussite—[$PbCO_3$] and hydrocerrussite—[$Pb_3(CO_3)_2(OH)_2$]. These mineral crystals were not observed on the BC or AC after Pb adsorption. It concluded that the lead adsorption capacity of DBC also depends partly on the precipitation mechanism. The precipitation of cerrussite and hydrocerrussite on DBC surface is due to the presence of specific organic functional groups (O=C=O) and high pH. Another study by Yao et al. (2011) proposed the predominance of adsorption over precipitation mechanism during the phosphate removal from aqueous solutions. High metal removal efficiency of biochar made from digested biomass suggests that it could be considered an efficient method of "biological activation" to produce biochar-based adsorbents.

3 Effect of Biological Modification

3.1 On Microbial Properties

Biochar application in soil induces the stabilization of organic matter and the exchange of electrons between microbial cells and organic matter (Fang et al. 2014). It can significantly affect the enzyme activities and community structure of microbes. These parameters can be examined using quantitative real-time polymerase chain reaction (q-PCR), ergosterol extraction, next-generation sequencing, phospholipid fatty acid quantitation (PLFA), gradient gel electrophoresis (DGGE), and fluorescence in situ hybridization (FISH) (Chen et al. 2013; Hale et al. 2014; Mackie et al. 2015; Rousk et al. 2009). Actinobacteria, Acidobacteria, Verrucomicrobia, and Gemmatimonadetes were observed to adopt high-throughput sequencing techniques in biochar-treated soils (Mackie et al. 2015; Nielsen et al. 2014). The different theories for the effect of biochar on microbial activity are explained by several researches. The first concept is that the high specific surface area with well-developed pore structure avails vacant space for microorganisms (Quilliam et al. 2013). Another research by Joseph et al. (2013) stated that the microorganisms extract the essential nutrients for their development from biochar. The biochar enhances the properties of substrate (such as pH, moisture, and aeration conditions) to alter its habitation (Quilliam et al. 2013). Another theory identified that biochar minimizes the toxicity to microorganisms by adsorbing the soil pollutants (Stefaniuk and Oleszczuk 2016).

3.2 On Biochar Properties

Biochar consists of various essential nutrients such as sodium, potassium, nitrogen, magnesium, and phosphorus for the enrichment of soil nutrients (Chathurika et al. 2016). With enriched soil nutrients, the rhizobacterial population increases which further leads to higher enzyme availability in soil. The enzyme adsorption depends on surface functional groups of biochar. The force (other than Coloumb force) between neutral protein molecules and polar disaccharides is linked to the neutral region of biochar surface. It leads to the biological activation of biochar through enzymes (Lammirato et al. 2011). Also, the biochar surface contains a significant amount of microalgae variants (Klebsormidium flaccidum and filamentous Cyanobacteria) that increase the activation process. Some extracellular enzymes (oxidoreductase enzyme) bind covalently with biochar surface and this biologically modified biochar can be efficiently implemented for heavy metal adsorption (Naghdi et al. 2018). The microbial activation is limited to bench-scale studies and biological activation of biochar through earthworms is been considered as a cost-effective method.

4 Mechanisms Involved in Biological Modification of Biochar

4.1 Biological Modification Through Intestinal Enzymes of Earthworms

The posterior part of earthworms has several enzyme-secreting glands and discharged digestive enzymes break the fed organic matter (Kaushik and Garg 2004). The earthworms can consume a diverse variety of substrates that can be divided into three classes (anecic, epigeic, and endogeic) according to their feeding habits (Domínguez and Edwards 1997; Huang et al. 2014). Epigeic earthworms (such as Eisenia fetida, Eudrilus eugeniae, and Perionyx excavatus) are most efficient in the degradation of complex organic substances and are recommended for biological modification of biochar (Khatua et al. 2018; Karmegam et al. 2021; Ananthavalli et al. 2019). Figure 2 depicts the process of biological modification of biochar by earthworms. The biological modification takes place in two stages. In the first stage (active stage), earthworms grind the consumed material in gut section, the gut-secreted enzymes crack the complex substances, and in the second stage (maturation stage), the earthworm releases biologically modified biochar with humus like substance (Gomez-Brandon et al. 2011; Gomez-Brandon and Domínguez 2014; Lores et al. 2006). During the active stage, the consumed organic material gets ground in gizzard, gut epithelium releases multiple enzymes, and induces biochemical reactions (Nozaki et al. 2009) for different enzymes, microbes, beneficial nutrients, and biologically modified biochar

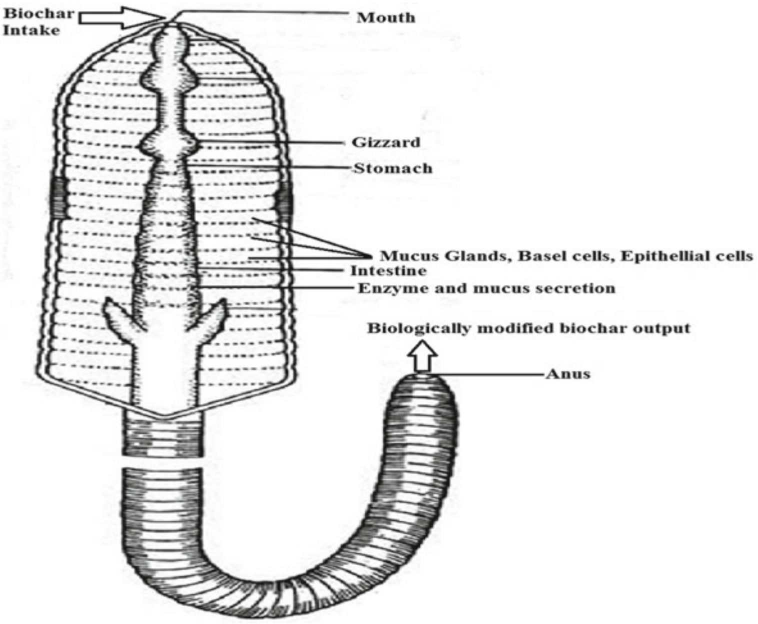

Fig. 2 Mechanism of biological modification of biochar by earthworms

(Balachandar et al. 2021; Domínguez et al. 2019). Therefore, the efficiency of vermicomposting increases by mixing organic waste with biochar (El-Naggar et al. 2019; Malinska et al. 2017). Along with the biological modification of biochar, the process also alters microbial properties by improving moisture availability, aeration level, toxicity adsorption, nutrient establishment, and pH neutralization (Ge et al. 2019; Zhu et al. 2017a, b; Quilliam et al. 2013; Ennis et al. 2012; Jeffery et al. 2011). The gut enzymes have various biomolecules which can be used as catalyst and affect soil pollutants (Burns et al. 2013; Gianfreda et al. 2016). The implementation of biochar increases the stability of enzymes and the biochar particles bind with extracellular enzymes due to highly affinitive surface functional groups. The ionic interactions and van der Waals forces are major contributors to binding (De Oliveira et al. 2000). It can be concluded from the above-mentioned studies that the co-implementation of biochar and earthworms is a feasible method for remediation of metal contamination. Various environmental researchers stated that the soil invertebrates (such as earthworms) efficiently produce biologically activated biochar with the use of gut enzymes. The experimental study of Zhu et al. (2017a, b) on cow manure-based vermi-modified biochar evidenced effective adsorption of Pb^{2+} and Cd^{2+} ions.

4.2 Biological Modification by Pyrolysis of Anaerobically Digested (AD) Biomass

The anaerobically digested waste can be efficiently converted to biochar by drying and pyrolysis. The studies concluded that the wood biomass components hemicellulose, cellulose, and lignin decompose at temperature ranges 200–325 °C, 240–375 °C, and 280–500 °C, respectively (Prins et al. 2006; Downie et al. 2009; Wani et al. 2021). The mechanism of biological modification by pyrolysis of AD biomass includes the degradation of different components (hemicellulose, cellulose, and lignin) present in the feedstock. The characteristics of resultant biologically modified biochar depend greatly on pyrolysis temperature, heating rate, heating time, raw material characteristics, inert gas flow rate, etc.

5 Applications of Biologically Modified Biochar

Biochar-based nanocomposites have been extensively utilized in heavy metal adsorption (for example, As(III), As(V), Pb(II), Cr (VI), Cd(II), Cu(II), and Hg(II)) from wastewater. The adsorption capacity of various inorganic contaminants vary with different nanomaterials, contaminant concentration, and biochar substrate (Li et al. 2016; Wang et al. 2017; Yao et al. 2013a, b; Zhang and Gao 2013; Zhang et al. 2013). Biologically modified biochar is generally used in advanced water remediation for biodegradation and adsorption of organic, inorganic, and biological contaminants which cannot be separated in primary and secondary water remediation (Çeçen and Aktas 2011) (Table 1).

With increased population and food demand, the use of chemicals in agricultural sector has been significantly increased in past decades. Therefore, there is a need to develop a safe and efficient soil remediation technique for contaminated soil. It is been evident from several studies that biochar with high specific surface area, oxygen containing surface functional groups, cation exchange capacity can be efficient inactivating, stabilizing, and adsorbing agent for even highly heavy metals concentrated soils (Beesley et al. 2011; Park et al. 2011; Uchimiya et al. 2010a, b, 2011a). The heavy metal stabilization capacity is higher for alkaline soil pH and higher intraparticle diffusion (Rees et al. 2014). The pristine biochar constitutes good adsorption capacity for heavy metals which significantly increases upon biochar modification. There are some lab scale observations on heavy metal adsorption using modified biochar but large-scale experimentation is still rare. Traditional technologies (precipitation, ion exchange, packed-bed filtration, electro-coagulation, membrane filtration) for heavy metal removal from wastewater were found to be effective in reducing pollutant concentrations. Though, these technologies involve high-cost and disposal problems. The bio-adsorbents are suggested as low cost alternative for wastewater treatment (Demirbas 2008; Sud et al. 2008).

Table 1 Biologically modified biochar for pollutant removal

S. No	Raw material	Characteristics of modified biochar	Pollutant	Remediation technique	Contaminant removal efficiency and mechanism	References
1	Anaerobically digested dairy waste residue	SSA—128 m^2/g Pore diameter—0.034 cm^3/g	Heavy metals (Pb^{2+}, Cu^{2+})	Mixing in digestion vessels	Removal efficiency 99% (Combined adsorption and precipitation)	Inyang et al. (2012)
2	Anaerobically digested sugar beet residue	SSA—555 m^2/g Pore diameter—0.147 cm^3/g	Heavy metals (Pb^{2+}, Cu^{2+}, Ni^{2+}, Cd^{2+})	Mixing in digestion vessels	Removal efficiency $\geq$97% (Combined adsorption and precipitation)	Inyang et al. (2012)
3	Anaerobically digested bagasse	SSA—17.7 m^2/g Pore diameter—0.147 cm^3/g	Pb^{2+}	Batch experiments by mixing in plastic vials	Removal capacity 653.9 mmol/ kg (Combined adsorption and precipitation)	Inyang et al. (2011)
4	Anaerobically digested sugar beet tailings	SSA—449 m^2/g	PO_4^{3-}	Digestion vessels	Mono-nuclear and poly-nuclear adsorption	Yao et al. (2011)
5	Wheat straw	SSA—190 m^2/g Pore diameter—2 nm	As(III)	Batch filtration	Removal efficiency 90–95% (Combined biofilm biosorption and biochar adsorption)	Zhu et al. (2018)

(continued)

Table 1 (continued)

S. No	Raw material	Characteristics of modified biochar	Pollutant	Remediation technique	Contaminant removal efficiency and mechanism	References
6	Pine-spruce wood biochar	SSA—184 m^2/g	Chemical oxygen demand (COD), ammonium nitrogen (NH4-N), total nitrogen (Tot-N), total phosphorus (Tot-P) and phosphate (PO4-P) from municipal wastewater	Column filters of biochar	COD 94–99% NH4-N 50% Tot-N 50–52% Tot-P 90–96% PO4-P 82–90% (Combined biosorption, biodegradation, and adsorption)	Perez-Mercado et al. (2018)
7	Aspen wood biochar	SSA—4 m^2/g Pore volume (V_t)—0.01 cm^3/g	Naphthenic acid removal in presence of As, Fe, Al	Effluent oil sand process wastewater	Naphthenic acid removal efficiency 34% (Combined biosorption, biodegradation and adsorption)	Frankel et al. (2016)
8	Softwood biochar	SSA—189 m^2/g V_t—0.12 cm^3/g	Naphthenic acid removal in presence of As, Fe, Al	Effluent oil sand process wastewater	Naphthenic acid removal efficiency 87% (Combined biosorption, biodegradation and adsorption)	Frankel et al. (2016)
9	Quercus wood biochar	SSA—210–250 m^2/g V_t—0.12–0.13 cm^3/g	Organic content from urban and synthetic wastewater	Snorkel bio-filters wastewater treated at two loading rates (170, 890 mg/l)	Organic content removal efficiency 92% (Bio-electrochemical interactions)	Prado et al. (2019)

(continued)

Table 1 (continued)

S. No	Raw material	Characteristics of modified biochar	Pollutant	Remediation technique	Contaminant removal efficiency and mechanism	References
10	Pine wood biochar	SSA—15 m^2/g	Fe(III)	Batch filtration	Direct interspecies electron transfer (DIET)	Chen et al. (2014)
11	Anaerobically digested waste water sludge	SSA—110 m^2/g	Fluoroquinolone antibiotics	Mixed in sealed flasks	Maximum adsorption capacity 19.80 mg/g (Adsorption)	Yao et al. (2013c)
12	Anaerobically digested bagasse	NA	Sulfamethoxazole (SMX) and sulfapyridine (SPY)	Mixed in digestion vessels	Maximum adsorption capacity 54.38 mg/g (SMX) and 8.60 mg/g (SPY)	Yao et al. (2017a, b)

Heavy metal contamination in soil has been a serious environmental problem in recent time (Alloway 2013). Biochar is generally an alkaline substance which can increase soil pH and promote stabilization of heavy metal contamination. Biologically treated biochar have significantly higher specific surface area and microbial biofilm which provide high pollutant adsorption capacity (Ahmad et al. 2014). Apart from adsorption, application of biologically treated biochar is also beneficial for agricultural soil due to increased microbial growth, bio-adsorption, and degradation of heavy metal and organic pollutants. The biologically modified biochar helps in retaining the soil nutrients (Yao et al. 2011).

6 Advantages and Limitations of Biological Modification of Biochar

The biologically modified biochar is not only a potential substitute for activated carbon in environmental remediation but also avails an additional advantage of sustainable carbon sink (Yoder et al. 2011; Laer et al. 2015). The contaminant removal efficiency of activated carbon, biochar and biologically modified biochar differ significantly due to dependence on adsorption capacity, bio-adsorption capacity, specific surface area, and pore size distribution. These parameters assert the suitability of biologically modified biochar due to high bio-adsorption, biodegradation, and adsorption along with positive environmental impact. The biological treatment of biochar is cost-effective and eco-friendly process as compared to physical and chemical activation. The other activation methods require high initial investment and produce secondary pollutants (emissions, chemical wastes, etc.) during activation (Sanchez-Hernandez et al. 2019). Also, there is no need for biochar regeneration after phosphate removal from soil because the phosphate-laden biochar consists of valuable nutrients and can be utilized as a slow-release fertilizer and for carbon sequestration (Yao et al. 2011). Thus, the implementation of biologically modified biochar eliminates the drudgery and cost associated with regeneration process.

7 Conclusions

This chapter summaries the feasibility, efficiency, and cost-effectiveness of biologically modified biochar. Raw materials and production process significantly alter the physicochemical and functional properties of biochar. Biologically modified biochar facilitates the effective biodegradation and biosorption through various complex mechanisms. The safe, cost-effective production process of biological modification avails agricultural, environmental, and economic sustainability. The co-implementation of earthworms and biochar is a feasible method for microbial growth, biochar modification, and soil nutrient enrichment. The biological modification of biochar through extracellular enzymes paved the path for efficient environmental remediation. There is a need for detailed study using statistical tools and mathematical modeling to accurately correlate the control parameters and properties of biologically modified biochar.

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