Biomaterial Biochar for Soil Carbon Sequestration Strategy and Its Future Prospects

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Abstract. Biochar has received a great deal of attention during the last few years. This multifunctional biomaterial has multiple modes of interactions and distinctive characteristics, which enable its wider applications such as in carbon sequestration, contaminant immobilization, greenhouse gas reduction, soil fertilization, water filtration, etc. Variability and predominance of a specific interaction are attributed to feedstock types and conditions of biochar production. Biochar is a product of burning waste organic matter such as wood, grasses, crop residues, lignite and manure, under conditions of limited oxygen during pyrolysis processes. The production of biochar from agricultural wastes is able to significantly reduce the volume and weight of the wastes. Because of this character, biochar is considered as a promising means for managing the biomass wastes. The changes in the ratios of H/C and O/C occurred during pyrolysis processes transform the molecular structures and arrangement of the atoms and result in high stability, aromaticity and recalcitrant characteristics of the biochar. Biochar can therefore keep carbon content for 100s–1000s years in soil which is crucial for soil health. Those biochar characteristics play beneficial role to mitigate CO$_2$ emission by enhancing long-term carbon sequestration and its strong sorption affinity for organic contaminants. The recalcitrant and longer life time nature of biochar draw carbon from the atmosphere and stabilize organic carbon in soil providing a carbon sink whilst improving water and soil quality. In this paper we discuss recent research development on biochar application for soil carbon sequestration and its future prospects. The results of our research on amendment of biochar from low rank coal lignite to the soil of palm oil plantation in stabilization of soil dissolved organic carbon are also discussed.

1. Introduction

Over the last 150 years, the increase of the amount of carbon in the atmosphere by 30% is parallel with the consumption of fossil-bearing fuels and other substantial sources such as land clearance and deforestation. Traditionally, carbon dioxide level in atmosphere fluctuated between 200 to 300 ppm, but since the industrial revolution time concentrations of the gas have been rapidly rising. Within the last 50 years alone, the concentration of carbon dioxide in atmosphere has increased by more than 36% (from 300 to 408 ppm) (http://www.co2.earth/). The accumulation of carbon dioxide in atmosphere has reached a millstone high above 400 ppm; an amount not seen in at least three to five million years. It is estimated that a prediction of 600–700 ppm at the end of this century would be achieved leading to an increased average surface temperature of 4.5–5°C (Anwar, et al., 2018).
Several studies have shown that cumulative recent anthropogenic carbon concentrations in atmosphere must be reduced and kept below a maximum upper limit to support earth’s life and reduce possible negative impact on environments (Woolf, et al, 2010). The Intergovernmental Panel on Climate Change (IPCC, 2014) recommended that greenhouse gas emissions must be lowered by 40-70% compared to 2010 values by mid-century, and to near-zero by the end of the century, to limit the increase in global mean temperature to 2°C.

One promising strategy is to restore and return the atmospheric carbon dioxide back into biomass and sequester the carbon in soil. This strategy utilizes organic wastes to produce biomaterial called “biochar” through pyrolysis process under limited/absent oxygen environment. Amendment of biochar to soil enables fractions of soil organic carbon to remain in the soil for longer period of times and thus reduces carbon dioxide production. This biochar amendment strategy also simultaneously enhances agricultural production as well as improvement in water holding capacity, porosity and aeration, etc.

The significance of soil organic carbon (SOC) in carbon sequestration primarily lies in its capacity to retain huge amount of carbon stock for longer period of times. For example, soil carbon stock of 2,500 petagram is the second largest global C after the oceanic pool (38,000 Pg), and it stores more than three times the amount of atmospheric C (750 Pg) and about 5 times the C stored in living biomass (Lal, 2008). However, fraction of SOC is suspected to decomposition and thus contributes to enhancement of atmospheric carbon dioxide. Under warmer climate and high humidity the degradation of SOC might be accelerated and results in large release of carbon dioxide to the atmosphere. Soil could therefore be a potential sink to restore atmospheric carbon dioxide but also a potential source of atmospheric carbon.

The basic idea of soil carbon sequestration is to retain in situ the existing soil organic carbon, absorb atmospheric carbon dioxide to soil systems, and stabilize them for a longer period of time and thus reduce carbon dioxide release to the atmosphere. Human activities such as transformation of forest to plantation, burning of fossil fuels, etc. have however shifted the nature of balanced C cycle by releasing more carbon to the atmosphere rather than absorb the gas back to the soil systems. Carbon sequestration strategy could therefore be considered as a potential mean to offset the increase of atmospheric carbon dioxide concentration (Oliviera, et al., 2018).

Application of biomaterial biochar for soil carbon sequestration has received increasing attention in the last few years due to its outstanding advantages with some additional benefits (Ahmad et al., 2014). More importantly, the amount of raw organic waste materials for biochar production is abundantly available in surrounding environments. Annually, around 6 billion tons of biomass generated by photosynthesis becomes agricultural wastes (Zhang, et al., 2013).

Scientific community in general has a consensus that biochar application to soil at a specific site contributes to sustainability of carbon sequestration and concurrently improves soil function while avoiding short- and long-term detrimental effects to the wider environment as well human and animal health (Oliveira, et al., 2018). In this paper recent research development on biochar production, application for carbon sequestration, its future prospects and the results of low rank coal lignite biochar amendment in the soil of palm oil plantation in stabilization of soil dissolved organic carbon are discussed.

2. Biochar production and properties

2.1 Production of biochar
Biochar production was an ancient practice by Egyptian over 70 centuries but its production was not the main target. Liquid wood tars produced from charring processes were used for embalming (Spokes, et al., 2012); a process for preserving human remains. In this ancient practice, “char” making biomass was buried underground. Because of self-sustaining nature of the method and low temperature of reaction, this ancient “char” making processes could carry on for days.

Similarly, biochar application as soil amendment first began over the past 2,500 years in South America (terra preta), the place which named “the black earth”. Biochar was created both naturally by forest fires and by human through burning bits for cooking and manufacturing. Acidic condition of terra
pretasoi in the past due to the high levels of toxic exchangeable Al hindered the agricultural practices. However, continuous application in the soil led to improvement of some physical properties of the soil and the increase in the soil pH levels. It was found that the terra preta soil could contain up to 50 Mg Cha⁻¹ in a form of biochar within approximately 1 m depth (Spokes, et al., 2012; Fuchs, et al., 2014).

Biochar is a carbon rich, fine-grained, porous material produced under oxygen-limited conditions and at temperatures between 350 and 700°C (Brassard, et al., 2016). It can also be defined as the solid residue obtained from the thermo-chemical decomposition or pyrolysis of plant and waste feedstock’s, and can be specifically used for application to soil as part of an agronomic, carbon sequestration or environmental rehabilitations. Simplification of biochar production can be illustrated in flaming match (see Figure 1). The flame provides heat and the resulting gases and vapors burn in the luminous zone in a process called flaming combustion, leaving behind char. When the match is put out, the remaining wood continues to pyrolyse, releasing a smoke composed of condensed tar droplets as it cools (Fuchs, et al., 2014).

A word of pyrolysis is used to describe breaking down (lysis) of a biomass material by heat (pyro). This word indicates two important aspects of biochar making; “heat” and “biomass”. In general, modern pyrolysis technology is divided to two major categories based on temperature of heating (Kambo and Dutta, 2015). Slow pyrolysis is conducted at a moderate temperature (350–550 °C) but longer residence time at limited/absent of oxygen environment with higher yield (30%) of biochar production. On the other hand, fast pyrolysis is performed at higher temperatures with upper temperature boundary 700-800°C at which the biochar surface area begins to decrease (Sulaiman, et al., 2016). During this fast pyrolysis, the combustion occurs more intensely compared to its counterpart and thus produces lower yield (12%) of biochar product (Inyang and Dickenson, 2015). Most of the biochar making methods are more convenient or less expensive than other types of carbon activation processes (Wang, et al., 2017).

During the pyrolysis processes, partial decomposition of molecules in the feedstock such as lignin, cellulose, hemi-cellulose, fat, and starch occurs; consequently the properties and composition of resulting biochar are pyrolysis type and feedstock dependent (Suliman et al., 2016). Oxygen-containing compounds naturally occurring on the biochar surfaces gradually decrease as the pyrolysis temperature increases. Slow pyrolysis produces a slightly negatively charged on the biochar surfaces and thus has a capacity to absorb positively charged cations. At higher pyrolysis temperatures (600°C or above) most of the oxygen-containing compounds are given off and the resulting biochar has a neutral to positively charged surface. Biochar produced with this fast pyrolysis has a lower cation exchange capacity. However, this type of biochar is preferred for agriculture applications because of its ability to hold and slowly release of cations (Windeatt, et al., 2014).

Controlling the pyrolysis temperature is an important and determinant parameter in biochar production. When the temperature increases, the amount of volatiles remaining in the biochar decreases. In this way, as the stable fixed carbon and ash contents increase, the stability and surface area of biochar produced will also increase. The surface area of biochar produced at lower temperatures (< 500°C) is in general below 150 m²/g depending also on the feedstock. Figure 2 shows fine shaving saw dust and its respective biochar product.
Other techniques of biochar making are also available such as hydrothermal carbonization and torrefaction. Hydrothermal carbonization is a chemical process to transform organic compounds to structured carbons at elevated temperature and pressure. Torrefaction is used to upgrade woody biomass primarily for reducing transportation costs due to moisture removal and increasing heating values (Spokes, et al, 2012). However, both techniques are not optimal options for biochar production because the oxygen to carbon (O/C) ratio of the resulting charred material is high between 0.4 and 0.6, indicating low aromaticity and stability characteristics of the resulted biochar (Oliveira et al., 2018).

### 2.2 Properties of biochar

Biochar is not a single and homogeneous entity but it is highly heterogeneous, both within individual biochar particles and mainly between biochar originating from different feedstocks and produced under different pyrolysis conditions. Partial decomposition of raw material gives off gases to atmosphere and remaining solid fraction is converted to the biochar product. Raw material is therefore an important aspect to consider in the biochar production. Some recent publications have shown evidence of biochar’s excellent ability to immobilize organic pollutants (Inyang, et al., 2014), inorganic pollutants (Li, et al., 2016; Qian, et al., 2016) and both contaminants (Chirakkara, et al., 2016; Liu, et al., 2017) in soil and water systems.

High capacity of biochar to immobilize organic and inorganic contaminants has been associated with the changes in various molecular structures and arrangement of their respective atoms in molecules after pyrolysis (Oliveira, et al., 2018). Figure 3 indicates that the changes in biochar molecular structures are reflected in the decrease of H/C and O/C ratios and polarity but the improvement of the aromaticity. The atomic ratios of H/C and O/C are typically correlated with the degree of aromaticity and polarity of biochar (Cantrell, et al, 2012). A molecule having high aromaticity possesses extra stability due to π bonds all lie within a cyclic structure and loop of p orbitals. P orbitals must be planar and overlap.
Van Krevelen diagram (Figure 3) shows that selective loss of the elements (C, O and H) occurring during the pyrolysis processes are not proportional. Removal of H and O atoms occurred more intense compared to the loss of C atom. As a consequence, a significant decrease in the ratios of H/C and O/C after the pyrolysis is observed. This occurs through the change in molecular structures and the rearrangement of atoms in the molecules. A newly formed molecule will have lower H and O atoms but high in C atom contents. This molecule (low H and O; high C contents) can be structurally planar with a resonance bonds exhibiting more stability than other geometric arrangements. Therefore, following the pyrolysis processes more stable molecule with high C content and aromaticity are formed. The presence of this molecule enhances the stability of the produced biochar (Windeatt, et al., 2014).

Aromaticity, stability and high C contents contribute to long lasting of the biochar in environments. Some reports indicate that components of the carbon in biochar are highly recalcitrant in soils, with reported residence times in the range of 100s to 1000s years; it is approximately 10-1000s times longer than residence times of most soil organic matter (SOM) (Fuchs, et al., 2014). Therefore, biochar addition to soil can provide a potential sink for carbon and contribute to the reduction of release greenhouse gases to the atmosphere.

Physical and chemical properties of biochar depend on operating conditions during pyrolysis and composition of the feedstock biomass (Wang, et al., 2017). For example, the proportion of cellulose, hemicellulose and lignin in feedstock biomass will influence the degree of reactivity and, hence, the degree to which the physical structure is modified during pyrolysis processing. Hemicellulose and cellulose are degraded at 200-300 and 300-400 °C, respectively, and lignin is degraded between 200 and 700 °C, representing a wide range of temperatures (Brassard, et al., 2016).

In addition, some external parameters that influence the psychophysical properties of biochar produced from any given biomass feedstock include heating rate, highest treatment temperature, pressure, and reaction residence time. Reaction vessel design, the flow rate of inert carrier gas, and the post-pyrolysis treatment (crushing, sieving activation, etc.) are all affected the resulted biochar.

Figure 4. Biochar characteristics and suitability for specific applications (Oliveira, et al., 2017)

High stability and aromaticity enriched with carbon, functional groups and ash contents, wide surface area, recalcitrant in nature and high water holding capacity provide biochar with various properties and thus promote a number of applications (Ahmad et al., 2014, Cantrell, et al, 2012, Windeatt, et al., 2014, Oliveira, et al., 2018). However, heterogeneity in nature and complex properties of this multi-functional biomaterial lead to difficulties in identifying specific mechanisms behind its numbers of reported effects; however it also provides opportunity to engineer its properties that best suite a particular site and purpose of applications. Various mechanisms of biochar interactions with organic and inorganic contaminants (Oliveira, et al., 2017) as given in Figure 4 and Figure 5 show flexibility of the biochar applications.

The removal mechanisms are often governed by the interactions of certain targeted pollutants with various attributes of biochar. For organic pollutants, the removal is primarily via chemisorption
(electrophilic interaction) and physisorption (e.g., pore diffusion, hydrophobic, electrostatic attraction/repulsion via π-π electron donor-acceptor, and H-bonding) through COOH, OH, and R-OH functional groups (Ahmad et al., 2014; Oliveira, et al, 2018). Moreover, other mechanisms including partitioning (in non-carbonized phase due to the reduction of substrate polarity), chemical transformation (via reductive reactions or electrical conductivity), and most of the bonded pollutants are ultimately mineralized via biodegradation (by diverse microorganisms present on the surface and in the micro-pores of biochar) (Ahmad et al., 2014).

Figure 5. Various mechanisms of biochar interactions with organic and inorganic pollutants (Oliveira, et al., 2017)

2.3 Biochar for soil carbon sequestration strategy

The current application of biochar to soil is modeled after the Amazonian Terra Preta soils, which have higher soil fertility compared to the surrounding soils and believed as the result of the presence “slash and char” to the soil (El-Nagar, et al., 2018). Biochar as a solid carbon product having high stability, aromaticity and recalcitrant in nature is potential mean to enhance soil health and increase agricultural yield by raising of soil pH and water holding capacity, harboring of microbes, improvement of cation exchange and nutrient retention capacity (Wang, et al., 2017).

Figure 6. Comparison of normal (a) and biochar carbon cycles (b) (adopted from)

Figure 6 provides a comparison between normal and biochar C cycles. Plants naturally absorb carbon dioxide via photosynthesis and transfer C into plant biomass. The dying plants eventually return the biomass to the soil and decompose. Net C withdrawal from the atmosphere is balanced by the release of
C from soil respiration and thus no net C withdrawal from the atmosphere is observed (see Figure 5a). In many cases, however, human intervention and activities accelerate the release of soil C to atmosphere and slow down the atmospheric C absorption due to e.g. deforestation. In this way, a negative C accumulation occurs. By converting biomass to biochar, the natural process of soil C decomposition is slowed down as fractions of the biomass in the soil are converted to more stable C-compounds. This will reduce the release of C to the atmosphere as shown in Figure 5b. The natural C cycle is interrupted as more stable fractions of C in the biochar are less accessible by soil microbes.

This indicates that the transferring of atmospheric CO$_2$ into other pools (e.g. soil), which stay in the soil for a longer residence time in such a manner that it is not re-emitted or reduces its release to the atmosphere in the near future, is called (soil) carbon sequestration. The term “soil carbon sequestration” is being used together to present a concept occurred in 1991. This concept is there for relatively new one (Feller and Bernoux, 2008). Recently, the term has been frequently used in association with biochar in many areas of applications including environmental remediation, agriculture practices, industries, waste management, soil amelioration, fertilizer, etc (Windeatt, et al., 2014; Wang, et al., 2017).

A strong association of soil C sequestration and biochar has been suggested by a number of researchers. Figure 7 shows CO$_2$ emission released by biomass (raw material of biochar) and equivalent biochar produced from the same amount of raw biomass with time. It shows that transforming biomass e.g. Organic wastes to biochar reduces CO$_2$ emission significantly. The CO$_2$ emission generated from decomposition of biomass occurs for a long period of times and decreases gradually; but the converted one in the form of biochar is stabilized in the soil and generates less CO$_2$ emission. Because of the long residence time in soil and the positive effects on soil properties, addition of biochar has been suggested as a way to sequester carbon from the atmosphere (Kambo and Dutta, 2015; Oliveira et al., 2018).

Biomass from decaying plants or remnants of agriculture can be converted into biochar that can help prevent “…global climate change by displacing fossil fuel use, by sequestering carbon into soil carbon pools and by dramatically reducing emissions of greenhouse gas carbon dioxide”. Biochar slows down the decaying and mineralization of the biological carbon cycle to establish a carbon sink and a net carbon withdrawal from the atmosphere of 20 percent.

![Figure 7. CO$_2$ emission generated from decomposition of biomass and equivalent biochar against time](image)

It is recommended that biochar application for soil C sequestration is used in association with agricultural practices as it is an effective mean and low cost strategy with numerous benefits. However, promotion of Sequestration in agricultural practices is urgently needed to ensure successful implementation as only 7 percent of the worldwide cropland areas adopted this practice. In addition, this strategy can potentially increase agronomic production while improving soil and environment quality,
enhancing the resilience of ecosystems and reducing its vulnerability, as well as mitigating climate change with soil C sequestration.

Assuming a total area of 1411 million ha cropland globally, the estimated global capacity for storing biochar-carbon would be up to 110 giga-ton with rate application of 10–100 mega-gram per ha biochar. The estimation of C stored in biochar can prevent the emission of 0.1–0.3 billion tons of CO$_2$ per year (Liu et al., 2015). Biochar can store about 50% of the plant’s original CO$_2$. Furthermore, replacing the slashing and burning of forests with charring can reduce CO$_2$ emissions by approximately 8 parts per million in half a century.

Field application of biochar in the soils for long period of time as given in Figure 8 can improve the soil physical properties, such as porosity and hydraulic conductivity of the soil.

![Figure 8](image)

Figure 8. (a) Porosity of macro-pores and (b) unsaturated hydraulic conductivities for the soils of control (S) and biochar amendment (SBC) after two years of field ageing (Liu, et al., 2019).

There are some concerns on the effectiveness of biochar application in soil as “priming effect” complicates any efforts to sequester carbon. A number of studies have observed an increase in the rate of organic matter decomposition following biochar application. However, some recent studies reported that significant decreases on DOC released from runoff compared to the soil with no biochar treatments (Eykelbosh et al., 2015; Liu et al., 2019).

2.4 Biochar for stabilisation of soil DOC

In addition to its cropland applications biochar could also be used for stabilization of dissolved soil organic carbon to reduce C loss to atmosphere. Dissolved organic carbon (DOC) in soils is operationally defined as the organic matter remaining in solution after 0.45 μm filtration (Liu, et al., 2019). It represents high mobility and bioavailable fraction of soil organic matter and plays an important role in transporting substances such as nutrients and contaminants in the soils.

Biochar application to soil affects DOC leaching behavior but varying results were reported. Beck et al. (2011) reported that the reduction about 67–72% of total organic carbon released from the biochar-treated soil into the rainfall runoff. Similarly, reducing effect was also observed for agricultural soils (Eykelbosh et al., 2015). Recent study conducted by Liu et al., (2019) observed that total discharge of the surface runoff from the biochar treated plots was significantly lower than the control plots. An
average 18% decrease for the surface runoff of the total DOC flux was observed for the biochar treated soil.

Our study on biochar amendment to the soil of palm oil plantation also confirmed positive effects of biochar amendment on stabilization of the soil DOC. This was reflected by the reduction of the soil extractable DOC in the soils at varying incubation time (see Figure 8). The biochar used in this study was made of low rank coal lignite which is widely available in some areas of abandoned coal mining in Jambi Province. This finding promotes for lignite biochar application for improvement of DOC contents in the soils of palm oil plantation where the area of oil palm plantation in Jambi Province has increased significantly within the last ten years (Dinas Perkebunan Propinsi Jambi. 2015).

**Figure 9.** effects of biochar amendment (0, 2, 5, 10 and 15%) on the soil of palm oil plantation and incubation time (week) on stabilization of soil dissolved organic carbon.

In this study, soils (750 g) of palm oil plantation were mixed with biochar (0%, 2%, 5%, 10% and 15%) in 1000-ml amber glass bottles and added with deionized water up to 70% of its water holding capacity. The sealed bottles were incubated for 2 months at room temperature (27 ± 3 °C). The bottles were regularly opened to ensure oxygen is not a limiting factor in this experiment. Fractions of the soil sub sample (5 g) were taken out every week and analyzed for dissolved organic carbon (DOC) after extraction with deionized water. Figure 9 shows the effect of lignite biochar amendment on stabilization of DOC in the soil of palm oil plantation.

Similar results have been reported by many authors (Suliman at al., 2016; Inyang and Dickenson, 2015; Cantrell at al., 2012). However, those studies mostly used biochar made of organic waste origin such as saw dust, wood, grasses, crop residues, manure, agricultural wastes, organic rubbish, etc.

2.5 Conclusion and recommendation

The application of biochar in the soil is an old technology that had been used for centuries. Complex properties owned by biochar such as high stability, aromaticity, recalcitrant in nature, high surface area, functional groups and ash contents are beneficial for improvements of soil properties and soil carbon sequestration. Amendment of biochar to the soil of agriculture practices has been seen as a promising strategy for soil carbon sequestration. The abundances of organic wastes available in environments could be used as biochar raw-making materials and thus promoting of wide ranges of application are possible.

Our study shows that the amendment of biochar from low rank coal lignite improves the fraction of DOC stabilization in the soil of palm oil plantation. It is recommended to promote low-rank coal lignite as raw material which is widely available in some areas of Jambi Province for biochar production.
References

[1] Ahmad M, Rajapaksha AU, Lim JE, Zhang M, Bolan N, Mohan D, Vithanage M and Lee SSand Ok YS 2014 Biochar as a sorbent for contaminant management in soil and water: a review Chemosphere 99 pp19–33
[2] Anwar MN, Fayyaz A, Sohail NF, Khokhar MF, Baqar M, Khan WD, Rasool K, Rehan M and Nizami AS 2018 CO$_2$ capture and storage: A way forward for sustainable environment. Journal of Environmental Management 226 pp131–144
[3] Beck DA, Johnson GR, Spolek GA 2011 Amending green-roof soil with biochar to affectrunoff water quantity and quality Environ Pollut 159 pp2111–2118.
[4] Cantrell KB, Hunt PG, Uchimiy M, Novak JM and Ro KS 2012 Impact of pyrolysis temperature and manure source on physico-chemical characteristics of biochar Bioresour Technol 107 pp419-428
[5] Chirakkara R, Cameselle C and Reddy KR 2016 Assessing the applicability of phytoremediation of soils with mixed organic and heavy metal contaminants Rev Environ Sci Biotechnol; 15 pp299–326 DOI 10.1007/s11157-016-9391-0
[6] Dinas Perkebunan Propinsi Jambi 2015 Luas Areal (Jambi)
[7] Eykelbosh AJ, Johnson MS and Couto EG 2015 Biochar decreases dissolved organic carbon not nitrate leaching in relation to vinasse application in a Brazilian sugarcane soil J Environ Manag 149 pp9–16
[8] Feller C and Bernoux M 2008 Historical advances in the study of global terrestrial soil organiccarbon sequestration Waste Management 28 pp734–740
[9] Fuchs M, Garcia-Perez M, Small P and Flora G 2014 Campfire Lessons - breaking down the combustion process to understand biochar production The Biochar Journal (Switzerland: Arbaz)
[10] Inyang M and Dickenson E 2015 The potential role of biochar in the removal of organic and microbial contaminants from potable and reuse water: review Chemosphere 134 pp232–240
[11] Kambo HS and Dutta A 2015 A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications Renew Sust Energ Rev 45 pp359–378
[12] Li H, Liu Y, Chen Y, Wang S, Wang M, Xie T and Wang G 2016 Biochar amendment immobiles lead in rice paddy soils and reduces its phytoavailability www.nature.com/DOI: 10.1038/srep31616
[13] Liu C, Wang W, Li P, Xian Q and Tang X 2019 Biochar's impact on dissolved organic matter (DOM) export from a cropland soil during natural rainfalls Science of the Total Environment 650 pp1988–1995
[14] Liu WJ, Jiang H and Yu HQ 2015 Development of biochar-based functional materials: Toward a sustainable platform carbon material Chem Rev 115 22 pp12251–12285
[15] Liu X, Sun J, Duan S, Wang Y, Hayat W, Alsaeedi A and Wang C dan Li J 2017 A valuable biochar from popla catkins with high adsorption capacity for both organic pollutants and inorganic heavy metal ions Scientific REPORTs 7: DOI:10.1038/s41598-017-09446-0
[16] Oliveira RF, Patel AK, Jaisi DP, Adhikari S and Lu HandKhanal SK 2018 Review Environmental application of biochar Current status and perspectives Bioresource Technology
[17] Qian T, Wang Y, Fan T, Fang G and Zhou D 2016 A new insight into the immobilization mechanism of Zn on biochar: the role of anions dissolved from ash www.nature.com/DOI: 10.1038/srep33630
[18] Suliman W, Harsh JB, Abu-Lail NI, Fortuna AM, Dallmeyer I and Garcia-Perez M 2016 Influence of feedstock source and pyrolysis temperature on biochar bulk and surface properties Biomass Bioenerg 84 pp37–48
[19] Wang B, Gao B and Fang J 2017 Recent advances in engineered biocharproductions and applications Critical Rev Environ Sci and Tech DOI: 10.1080/10643389.2017.1418580
[20] Windeatt JH, Ross AB, Williams PT, Forster PM, Nahil MA and Singh S 2014 Characteristics of biochars from crop residues: Potential for carbon sequestration and soil amendment J. Envi Manage 146 pp189–197

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