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Review Article

A Review of Biochar Based Technologies in Carbon Capture and Sequestration

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Abstract

The emission of greenhouse gases, predominantly, carbon dioxide, due to burning, decomposition and various other ways to dispose of agricultural crop residues or biomass waste has led to an increased persistence of carbon dioxide in the atmosphere. Biochar is biologically active charcoal which is created by biomass feedstock pyrolysis in an oxygen deprived condition. Feedstock such as manure generated by poultry and livestock operations, agricultural waste and biodegradable solid waste can be used for the production of biochar. Biochar can be used as a soil amendment for poor soils, carrier for plant nutrients, water filtering medium, insulation in the building industry and as carbon sinks due to its porosity, stability and high surface area. The pyrolysis of biomass in the absence of oxygen yields an array of solid (biochar - dominant product during slow pyrolysis), liquid (bio-oil) and gaseous (syngas) products. As the key element in a new carbon-negative strategy, biochar can mitigate climate change by carbon sequestration and facilitate the development of a sustainable society by resolving critical challenges of food and energy security, etc. This review emphasizes on biochar utility as an approach to carbon capture and sequestration and hence the need to develop a carbon negative industry by minimizing atmospheric carbon.

Keywords: Agricultural waste, Biochar, Carbon dioxide emission, Carbon capture and sequestration, Climate change mitigation, Feedstock, Pyrolysis, Soil amendment

Introduction

Carbon dioxide produced during burning of wastes has a significant role in increasing Global warming. CO_2, CH_4, N_2O, chlorofluorocarbons and water vapors are the major greenhouse gases having a share in Climate change and Global Warming.[13] The amount of Carbon dioxide in the atmosphere can be considerably reduced if this carbon is captured and stored within the soil masses using a process known as Carbon Sequestration. Carbonization of organic wastes to biochar has been suggested to minimize the negative impacts of direct burning of such wastes.[1]

Biochar is the major product obtained during the pyrolysis of biomass in the absence of oxygen at a particular temperature. This thermal decomposition yields three products namely biochar, bio-oil and syngas.[2] Pyrolysis is the heating of biomass in an oxygen- limited atmosphere, causing release of volatile C structures, hydrogen (H), methane (CH_4) and carbon monoxide (CO). The volatile C structures (alcohols, oils, tars, acids, etc.) can be re-condensed as bio-oil. The biochar that remains consists mainly of C, and contains some O, H, N and ash [calcium (Ca), potassium (K), etc.].[22] Syngas containing gases like H_2 and CH_4 can be used as a fuel for combustion of biochar in future or as a renewable energy source.

This process of thermal decomposition often mirrors the production of charcoal, which is one of the most ancient industrial technologies developed by mankind. However, biochar can be distinguished from charcoal and similar materials in that it is produced with the intent, it be applied to soil as a means of improving soil productivity, carbon (C) storage and possibly filtration of percolating soil water (to try and cut pollution of surface and groundwater bodies). The production process and the intended use, forms the basis for distinguishing biochar.[16]

Biochar, due to its chemical and physical properties has proved to be an efficient carbon sequestering agent in soil mass. A characteristic of biochar that is common to char in general is that it comprises mainly stable aromatic forms of

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organic carbon, and, compared to the carbon in a pyrolysis feedstock, cannot readily be returned to the atmosphere as CO_2 even under favorable environmental and biological conditions, such as those that may prevail in the soil.[16]

Applications of biochar are currently limited to agriculture such as improving soil nutrient retention capacity, water holding capacity, soil productivity, soil quality, nutrient cycling, bioavailability for plants and stabilization.[2, 28] Apart from agriculture, uses of biochar fall into four main categories: climate change mitigation, soil conditioning, waste management, and energy, and these may overlap as there is great potential for synergies in application.[29] This review analyses the role of biochar-based technologies in Carbon Capture and Sequestration.

Characteristics and Potential of Biochar

Feedstock suitable for producing biochar include biomass such as poultry waste, green waste, forestry waste, poultry litter, wood, sewage, sludge, manure, rice husks, straws, paper mill waste, cane trash, bagasse, etc. Biochar essentially differ in their chemical and physical and chemical characteristics depending upon their feedstock and processing conditions.[35]

Physical: The physical properties of biochar help in finding a viable solution to various environmental problems. The site of application of biochar is determined by the chemical and physical characteristics of biochar. The nature of the feedstock (organic biomass) and the pyrolysis method are of utmost importance in determining the physical properties of biochar such as the carbon content, ash content, surface area, surface morphology and its quality as a soil amendment.[21] The physical properties of biochar depend largely upon the chemical composition of the feedstock which is noticeable in the final product.[22]

The affinity of nutrients to biochar and its stability in soil for thousands of years makes it a potential means to sequester carbon. Biochar is highly porous resulting in high water retention capacity. Biochar being highly absorbing, retains the soil nutrients in addition to adsorbing the impurities thus, preventing water contamination.[31] Biochar produced at high pyrolysis temperature has higher carbon stability compared to that obtained at low temperature. Under such conditions, biochar may also possess a higher carbon sequestration potential when applied to soil.[1]

Structurally, biochar is composed of condensed aromatic carbon rings.[3] The surface area of biochar made by fast pyrolysis is found to be low. Thus, the physical properties of biochar made under fast pyrolysis are found to be different than the one produced by slow pyrolysis. The specific surface area of biochar is found to be higher than sand and clay when added as an amendment.[28] Pyrolysis tests conducted on several feedstock show that degradation of hemicellulose occurs at 200°C- 260°C and that of lignin and cellulose at 280°C-500°C and 240°C-350°C respectively. Results show that coconut shell-based biochar and wood pellet-based biochar have the maximum percentage carbon by weight.[3]

Chemical: Chemically, biochar does not have a fixed composition except the general structure of its organic portion consisting of aromatic carbon rings with very high carbon content.[21] The chemical properties including pH, electrical conductivity, ash content, carbon stability, surface area, cation exchange capacity, volatile material, basic functional groups, etc. show variation with the pyrolysis conditions and the composition of the feedstock.[1]

Studies project that there is higher carbon stability (large amount of fixed carbon content) in case of biochar produced at high pyrolysis temperature as compared to those produced at relatively lower temperatures. The former thus, has greater carbon sequestration capacity.[8] In case of Rice-straw derived biochar, an increase in the charring temperature lead to an increase in the aromaticity of carbon and a corresponding increase in its recalcitrance.[34] The fixed carbon content, volatile material, ash content and biochar yield showed remarkable change with variation in temperature from 300°C to 400°C.[17]

Next is the surface phenomenon observed with the highest treatment temperature. Peak surface area of biochar is obtained between 650°C and 850°C for different types of biochar from different feedstock and highest treatment temperature value must be greater than 500°C for obtaining large surface area of biochar. This increase in surface area is in response to volatilization of organic compounds that otherwise clog the pores of biochar.

High surface area, high pH, and high cation exchange capacity are desirable properties for soil amendment. In case of wood-derived biochar this condition is derived at a narrow temperature range of about 400°C to 450°C.[6]

Structure: Biochar structure can be analyzed using different analytical techniques such as SEM, TEM, XRD, ESR, Raman spectroscopy. These methods are the most commonly used ones for general characterization and identification of microstructure in the biochar. BET method can be used to analyze the surface area and pore structure of biochar.[17] The biochar resulting from biomass pyrolysis at highest treatment temperature results into a complex aromatic ring structure with increasing sheets of conjugated aromatic carbon and three-dimensional graphite structure.[3]

Biochar for Carbon Capture and Sequestration the Carbon Cycle

Carbon moves in a cyclic form in the ecosystem getting transformed into different forms during its journey, having sources and sinks.[4] It is stored in the atmosphere, land biota, rocks, soil and fossil fuels, ocean biota, water and sediments (Center for Environmental Visualization n.d.) Carbon is produced by natural and anthropogenic sources.[4] Apart from natural sources which include respiration and biomass decomposition, it is the anthropogenic sources i.e. industrialization, deforestation and fossil fuel burning which has caused an increase in the percentage of carbon in the ecosystem. The current percentage of atmospheric carbon dioxide is 0.04%.[27] It is recorded that the flux out of fossil fuels is 60,000 times faster than the flux into it (Center for Environmental Visualization n.d.). As a result of climate change and variability, the percentage of CO_2 that remains in the atmosphere has increased from 40% to about 45% in the past 50 years. The discharge of carbon into sinks (lands, forests and oceans) has significantly declined leading to increase in the fraction of carbon in the atmosphere.[25] Due to decline in the ability of natural sinks, the inclusion of artificial sinks is seen as an alternative to extract carbon from the atmosphere and store it within the Earth's crust.[30] Carbon capture and Sequestration is one such artificial technology to reduce atmospheric carbon concentrations.

Carbon Capture and Sequestration Technologies

Carbon capture and Sequestration is an emerging technology to reduce the effect of fuel combustion or industrial processes by extracting carbon dioxide from flue gases, compressing it, transporting it to suitable sites using pipelines and then storing it within deep geological formations preferably sedimentary rocks, such that all means of escape are prevented.[37]

CO_2 capture technologies can be classified based on a) the type of source which can be concentrated or distributed and b) the technique which may involve physical, chemical or biological methods. In case of concentrated or point sources, three methods are generally adopted namely, post-combustion, pre-combustion and oxy-fuel combustion. Technologies to capture carbon from distributed sources such as vehicles are still being researched.[10,23]

The second category comprises of capture technologies like physical absorption, physical adsorption, membrane separation cryogenic separation and biological capture processes.[38] Biochar is categorized as a biological process of carbon capture and is considered an economical method due to its utilization of biomass as feedstock.

Biochar Technologies

Feedstock for Biochar

Various waste materials from food crops, forest debris and other plant material are used as the major sources of biomass.[3] It was found that pyrolysis temperature and feedstock type are the most important factors in determining the suitable applications for the different types of biochar prepared through slow pyrolysis biochar.[32] The type of feedstock affects the production rate , thermal stability and elemental composition of char.[32] India, being agriculturally enriched, has copious amounts of agro residues like wheat straw, banana stem, sugarcane bagasse, sunflower stalk, sweet sorghum, weeds like Saccharum spontaneum, Typha latifolia, Eicchornia crassipes, Prosopis juliflora, Lantana camara which can be utilized to produce bioethanol.[12] The biochar production using pine wood chips, mixed larch and spruce wood chips and softwood pellets shows that the fraction of recalcitrant carbon in biochar increases with increasing pyrolysis temperature which means higher pyrolysis temperature: higher proportion of stable fraction in biochar.[18]

Production Technologies

Transformation Principles

At moderately high temperature in an inert atmosphere, pyrolysis thermally decomposes the carbohydrate structure of biomass into carbonaceous high-density solid residue (biochar), high density liquid (bio-oil) and low energy density gas (syngas).[14] The organic compounds are heated in a closed chamber with temperature more than 400 degree Celsius in the absence of oxygen due to which it decomposes and release a residual solid phase called biochar. The various process parameters such as temperature, heating rate, pressure, purge gas and particle size influence the properties of biochar.[14] Conventionally, slow pyrolysis is the preferred way to produce biochar while fast pyrolysis is the route for bio-oil.[36]

Table 1 differentiates the two pyrolysis processes.

Table 1.Conditions required for different pyrolysis processes

Process type	Temperature	Residence time	Final products	Solid product yield (Dry wood feedstock) (mass %)	Carbon content of solid product (mass %)	Typical carbon yield (mass carbon, product/ mass carbon, feedstock)	References
Slow-pyro lysis	~400ºC	Minutes to days	Bio-oil (30% includes 70% water), biochar (35%), syngas (35%)	≈ 30%	95%	0.2-0.26	(Meyer, Glaser, & Quicker, 2011), (Bhattacharya et al. 2015).
Fast pyro lysis	~500°C	~1s	Bio-oil (75% include 25% water), biochar (12%), syngas (13%)	12-26%	74%	≈ 0.58	(Meyer, Glaser, & Quicker, 2011), (Bhattacharya et al. 2015).

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Various technological challenges occur in the typical pyrolysis process while synthesizing biochar. High and controlled maintenance of heat rates is required. A mandatory check is required with feedstock with high chlorine content as the release of chlorine may result in corrosion of the reactor containment. Correct reaction temperature and rapid removal of char can be challenging in fast pyrolysis systems.[20]

Benefits, Potential for a Sustainable Society and the Future Prospects of Biochar Utilization

Biochar for a Sustainable Society

Utilization of biochar has many benefits for the development of a sustainable society, including (i) enhancing soil quality and crop production, (ii) as carbon sinks in soil through carbon sequestration and GHG balance (iii) turning bio-energy into a carbon-negative industry by collecting energy generated during pyrolysis processes.

Improvement in Soil Quality and Crop Production

A number of soil properties influence the soil fertility and involve complex balances of biotic and abiotic reactions. Immediate effects can be seen on properties of soil such as nutrition, water retention and microbial activity although these effects may vary on soil types.[11]

Biochar may also have long-term impacts on soil environment due to its recalcitrant nature. Soil forming processes that govern the transformation, accumulation and translocation of soil constituents can be influenced by biochar application. Hence, in the long-term, it can modify soil pedogenic activity, productivity and morphology.[35] Since biochar possesses a wide range of chemistries, there is limited accountability for different types of biochar in improving soil yields. Factors like soil nutrient status, absorption, release or catalyzing transformations of compounds that affect the plant and microbial growth, altered timings and rates of seed germinations as a function of biochar additions, etc. are responsible for biochar's effect on agronomic yield.

Biochar has a potential in bioremediation, increasing water holding capacity and reducing soil bulk density. Moreover, it helps to increase soil strength, available P, soluble Fe, exchangeable K, Al and Ca, porosity and soil pH.[19] The macropores in biochar are essential for vital functions of soil such as hydrology and aeration, movement of roots through soil and as habitats for a vast variety of microbes.[5, 16]

Biochar application is a 4,000-year old generational practice used for converting agricultural wastes into soil conditioners for better carbon storage. For example, the Terra Preta soil in the Amazon basin contains large amounts of charred materials, most likely added by pre- Columbian farmers who practiced slash and char agriculture, and improved soil properties and nutrient use efficiency which increases plant growth.[9]

Carbon Sequestration and GHG Balance

Biochar is produced by thermo-chemical conversion of biomass. Burning biomass in the absence of oxygen leads to the formation of biochar and products of incomplete combustion. The resulting biochar consists of mainly carbon and is characterized by a very high recalcitrance against decomposition. Thus, its non-fuel use would establish a carbon sink. The pyrolysis of biomass (mainly crop residue) facilitates bio-energy production and carbon sequestration if the biochar is re-distributed to the agriculture fields. Thus, the uses of crop residues as potential energy source or to sequester carbon and improve soil quality can be complementary, not competing uses.[15]

Climate Change Caused by Increase in the Atmospheric Concentration of Greenhouse Gases

Greenhouse gases (GHGs) is predicted to cause catastrophic impacts on our planet. This must therefore provide the incentive for action to reduce emissions and increase removal of GHGs from the atmosphere. Biochar acts in several ways to aid in climate change mitigation. Firstly, by the utilization of biochar in agriculture. Secondly, biochar in soil has the potential to reduce emissions of non-CO_2 greenhouse gases. The soil is both a significant source and sink for greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Biochar application to soil has been shown to affect carbon and nitrogen transformation and retention processes in soil. These processes along with other mechanisms, as influenced by biochar can play a significant role in mitigating soil GHG emissions.[11]

As biochar has been shown to increase biomass production by crop species, even more carbon is being taken out of the atmosphere and stored in plant tissue. Apart from obvious economic advantages of improved crop yields, this also increases the amount of waste biomass available for slow pyrolysis and bioenergy production, and increases the amount of biochar available to sequester carbon long-term.[35]

Bioenergy for a Carbon-negative Industry

Reducing carbon dioxide emissions may not be enough to curb global warming. The solution will also require carbon-negative technologies that actually remove large amounts of CO_2 from the atmosphere. Bioenergy produced from renewable biomass can replace fossil-fuel- based energy sources. The slow pyrolysis low-temperature system offers the distinct advantage that process conditions can be optimized for the recovery of biochar or syngas. It is assumed that the energy yield from the pyrolysis process is 50% of the energy contained in the feedstock if the system is optimized for syngas production and 38% where optimized for biochar production. As biomass breaks down into char, hydrogen, methane and other hydrocarbons are released and can be captured to refine into renewable fuels. Energy produced during pyrolysis can be turned into space heat, electricity, reformed into ethanol or ultra-clean diesel.[24]

Economics of Biochar

In spite of considerable scientific work on the effects of biochar application to soils with respect to crop yields, and the various other environmental benefits associated with carbon sequestration, the commercial production of biochar is very limited today.[8]

The capital costs of construction of pyrolysis power plants are rather uncertain as compared to operating costs. Both the fast and slow pyrolysis power plants are unprofitable under current conditions, the slow plants being less so due to higher value of energy sales and the added value of the biochar.[8]

Only when there is an investment from entrepreneurs, recognizing and valuing the environmental benefits along with profits, will the costs and prices of pyrolysis of biomass and the production of biochar be fully discovered, and technological innovations to lower costs and improve the product and process performance take place. An added advantage of biochar is that it is one of the few technologies to address climate change, and which creates net economic and environmental benefits.[33]

Conclusion

As a source for bioenergy and an alternative to reduce atmospheric carbon concentration, biochar holds significance in building a carbon-negative industry. Biochar is produced through the process of pyrolysis. The three main products of pyrolysis: liquid (bio-oil), biochar, and gas, can influence the global carbon cycle in two ways. First, all three pyrolysis products may be used as an energy source that can displace fossil energy use. Second, if the carbon-rich and stable biochar is produced from a biomass feedstock that removes carbon dioxide (CO_2) from the air via photosynthesis, which would otherwise have decomposed, then char-amended land becomes a carbon sink for more intensive and long-lasting carbon storage. Biochar consists of stable carbon rings and thus resists decomposition over long periods of time, making it a suitable additive for soil enhancement alongside producing energy. Biochar production from waste could reduce demand for fertilizers, cut dependency, cost and pollution, thus enabling the use of degraded land in a more efficient way. A recent global survey shows that the average price of pure biochar is INR 154.58/Kg, which is agronomically not affordable thus making the cost single most constraint in the uptake of the biochar industry.[26]

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Conflict of Interest: None

References

1. Al-Wabel MI, Al-Omran A, El-Naggar AH et al. Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from conocarpus wastes. *Bioresource Technology* 2013; 131: 374-9.
2. Barrow CJ. Biochar: potential for counter in gland degradation and for improving agriculture. *Applied Geography* 2012; 34: 21-8.
3. Bhattacharya I, Yadav JSS, More T et al. Biochar. Carbon Capture and Storage. 2015; 421-454.
4. Bolin B. The carbon cycle. *Scientific America* 1970; 223: 2-10.
5. Brewer CE. Biochar characterization and engineering. Graduate Theses and Dissertations, Iowa State University Capstones, Theses and Dissertations, 2012.
6. Budai A, Wang L, Gronli M et al. Surface properties and chemical composition of corncob and miscanthus biochars: effects of production temperature and method. *Journal of Agricultural and Food Chemistry* 2014; 62(17): 3791-99.
7. Mc Carl BA, Peacocke C, Chrisman R etal. Economics of biochar production, utilisation and GHG Offsetspr. International Biochar Initiative Conference, New castleupon Tyne, UK. 2008.
8. Cui Z. A review of biochar's applications in the soil nitrogen cycle. Department of Chemical & Material Engineering, New Mexico State University, 2015. Available from: http://chme.nmsu.edu/files/2014/11/CHE-498-Final-Report-Cui-S15.pdf.
9. Glaser B, Woods WI. Amazonian dark earth: explorations in space and time. *Springer-Verlag Berlin Heidelberg*, 2004: XIV, 216.
10. IEA. *Carbon capture and storage*. *International Energy Agency* 2017; 325: 1647-52.
11. IPCC. CO_2 removals in residual combustion products (charcoal): basis for future methodological development. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Available from: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_p_Ap1_Charcoal.pdf.
12. Gentela J, Prashanthi GS, Sravanthi K et al. Status of availability of lignocellulosic feed stocks in India: biotechnological strategies involved in the production of bioethanol. *Renewable and Sustainable Energy Reviews* 2017; 73: 798-820.
13. Lal R. Soil carbon sequestration to mitigate climate change. *Geoderma* 2004; 123(1-2): 1-22.
14. Lee Y, Park J, Ryu C et al. Comparison of biochar properties from biomass residues produced by slow pyrolysis at 500°C. *Bioresource Technology* 2013; 148: 196-201.
15. Johannes L, Gaunt J, Rondon M. Bio-char sequestration in terrestrial ecosystems - a review.

ISSN: 2455-3093
DOI: https://doi.org/10.24321/2455.3093.201806

Mitigation and Adaptation Strategies for Global Change 2006; 11(2): 403-27.

16. Johannes L, Joseph S. Biochar for Environmental Management. 2009. Available from: https://pdfs.sem anticscholar.org/1dcd/dcb78cb7010fedb248f8c1f402ed5a0a731c.pdf.
17. Wu-Jun L, Jiang H, Yu HQ. Development of biochar-based functional materials: toward a sustainable platform carbon material. *Chemical Reviews* 2015; 115(22): 12251-85.
18. Ondřej M, Brownsort P, Cross A et al. Influence of Production Conditions on the Yield and Environmental Stability of Biochar. *Fuel* 2013; 103: 151-5.
19. Agusalim M, Utomo WH, Syechfani MS. Rice husk biochar for rice based cropping system in acid soil 1. the characteristics of rice husk biochar and its influence on the properties of acid sulfate soils and rice growth in West Kalimantan, Indonesia. *Journal of Agricultural Science* 2010; 2(1): 39-47.
20. Sebastian M, Glaser B, Quicker P. Technical, economical and climate related aspects of biochar production technologies: a literature review. *Environmental Science & Technology* 2011; 45(22): 110930141845009.
21. Mukome FND, Zhang X, Silva LCR et al. Use of chemical and physical characteristics to investigate trends in biochar feedstocks. *Journal of Agricultural and Food Chemistry* 2013; 61(9): 2196-204.
22. Novak JM, Lima I, Xing B et al. Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. *Annals of Environmental Science* 2009; 3(843): 195-206.
23. Page SC, Williamson AG, Mason IG. Carbon capture and storage: fundamental thermodynamics and current technology. *Energy Policy* 2009; 37(9): 3314-24.
24. Introduction to carbon negative energy. Available from: https://gcep.stanford.edu/pdfs/TechReport2016/2.7.1_Intro_Carbon%20Negative%20Energy_2016.pdf.
25. Le Quéré C, Raupach MR, Canadell JG et al. Trends in the sources and sinks of carbon dioxide. *Nature Geoscience* 2009; 2(12): 831-6.
26. Singh B, Singh BP, Cowie AL. Characterization and evaluation of biochars for their application as a soil amendment. *Australian Journal of Soil Research* 2010; 48(6-7): 516-25.
27. Skog KE, Nicholson GA. Carbon cycling through wood products: the role of wood and paper products in carbon sequestration. *Forest Products Journal* 1998; 48(7-8): 75-83.
28. Sohi SP, Krull E, Lopez-Capel E et al. A review of biochar and its use and function in soil. *Advances in Agronomy* 2010; 105(1): 47-82.
29. Spokas KA, Cantrell KB, Novak JM et al. 2012. Biochar: a synthesis of its agronomic impact beyond carbon sequestration. *Journal of Environment Quality* 2012; 41(4): 973.
30. Lehmann J, da Silva JP, Steiner C et al. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. *Plant and Soil* 2003; 249 (2): 343-57.
31. Sukartono, Utomo WH, Nugroho WH et al. Simple biochar production generated from cattle dung and coconut shell. *Journal of Basic and Applied Scientific Research* 2011; 1(10): 1680-5.
32. Sun Y, Gao B, Yao Y et al. Effects of feedstock type, production method, and pyrolysis temperature on biochar and hydrochar properties. *Chemical Engineering Journal* 2014; 240: 574-8.
33. Peter W. Biochar and bioenergy production for climate change mitigation. *Science and Technology* 2007; 64(1): 5-10.
34. Wu W, Yang M, Feng Q etal. Chemical characterization of ricestraw-derived biochar for soil amendment. *Biomassand Bioenergy* 2012; 47: 268-76.
35. Van Zwieten L, Kimber S, Sinclair K etal. Biochar: potential for climate change mitigation, improved yield and soil health. Annual Conference of the Grass land Society of NSW. 2008 a: 30-33.
36. Mohan D, Pittman CU Jr., Steele PH. Pyrolysis of wood/biomass for bio-oil: a critical review. *Energy & Fuels* 2006; 20; 848–889.
37. ChenW. Carbon Capture and Sequestration. Available from: http://large.stanford.edu/courses/2010/ph240/chenw2/.
38. Theo WL, Lim JS, Hashim H et al. Review of pre-combustion capture and ionic liquid in carbon capture and storage. *Applied energy* 2016; 1(183): 1633-63.

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