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Biochar as Soil's Best Friend – A Review

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ABSTRACT

In order to deal with environmental sustainability issues such as global climate change, food and energy crisis as well as environmental pollution, biochar had been widely used as a tool to combat these problems. It might act as soil carbon sink to restore soil organic carbon (SOC) larger than its inherent capacity, thus reducing the emission of greenhouse gasses (GHGs). The high soil carbon storage, available nutrient elemental composition, high aromatic structure, high porosity, and high alkalinity of biochar are factors for it to act ideally as potential soil improver. Studies thus far have shown the properties of biochar and its effect on crops and ecosystems vary, mainly because of differences in biomass sources and production processes. The aim of this review paper is to summarise the benefits of applying the biochar from various sources in soil in order to overcome climate change and improve soil properties thereby increasing crop productivity.

ABSTRAK

Dalam usaha untuk menangani isu-isu berkaitan kelestarian alam sekitar seperti perubahan iklim global, bio-arang telah diberi pendekatan secara meluas sebagai satu kaedah untuk mengatasi perubahan iklim. Ia mampu bertindak sebagai penyimpan/penyerap karbon tanah secara lebih banyak daripada secara semulajadi bagi memulihkan karbon organic tanah (SOC), sekaligus dapat mengurangkan pelepasan gas rumah hijau (GHG). Sifat-sifat bio-arang termasuk penyimpan karbon tanah yang tinggi, terdapat komposisi unsur nutrien yang tersedia, terdapat struktur aromatik, tahap keliangan dan tahap kealkalian yang tinggi adalah antara faktor-faktor yang membolehkan bio-arang sesuai bertindak sebagai pembaik tanah yang berpotensi. Kajian-kajian sepanjang masa ini telah menunjukkan keputusan yang berbeza terhadap sifat-sifat bio-arang serta implikasinya terhadap tanaman dan ekosistem, sebahagian besarnya berpunca daripada sumber biojisim dan proses penghasilan yang berbeza. Oleh itu, tujuan rencana ini adalah untuk merumuskan kelebihan penggunaan bio-arang daripada pelbagai sumber dalam tanah untuk mengatasi perubahan iklim, memperbaiki sifat-sifat tanah di samping meningkatkan produktiviti.

Keywords: biochar, climate change, soil fertility, carbon storage.

INTRODUCTION

Biochar is not a new concept as its origin and history had been developed for centuries. It was started with the discovery of dark colored *Terra preta* soils, containing high concentrations of charcoal and organic matter throughout the Amazon Basin in Brazil about 2500 years ago. *Terra preta* (*Figure 1*) is well known for its high fertility soil amidst the highly weathered and acidic oxisols in the region, used to support Amazonians agriculture needs and yet covers nearly 10% of the Amazon Basin (Mann, 2005). It was reported that continuous cultivation had been practiced in *Terra preta* soil without fertilisation for over 40 years (Petersen *et al*., 2001). With more agriculture activities are made possible by *Terra preta*, studies on biochar application has been extensively approached since 1950s. It is an ancient practice of converting agricultural waste into soil enhancer that can hold carbon, boost food security and increase soil biodiversity. Alarming greenhouse gas (GHG) emissions also lead to biochar research because it can positively reduce the effects of global warming as reported by Fowles (2007), Lehmann (2007) and Lehmann *et al*. (2006).

Production of Biochar

Biochar is defined as a solid carbonaceous material prepared by a pyrolysis process to capture all end products for re-use as energy (Ertas and Alma, 2010; Islam *et al*., 2004; McKendry, 2002). Pyrolysis process is defined as a direct thermal degradation process of biomass in the absence of oxygen or presence of limited oxygen in specially designed furnace to obtain arrays of solid, liquid and gas products (US Biochar Initiatives, 2009). The quality and quantity of the final pyrolysed products (mainly pyrolytic oil (bio-oil), synthesis gas with different energy values (syngas) and solid residues (biochar) (Gaunt and Lehmann, 2008; Yaman, 2004)) are significantly influenced by the biomass sources and the pyrolysis process (*Table 1*). The process creates a fine-grained, highly porous charcoal that helps soils retain nutrients and water.

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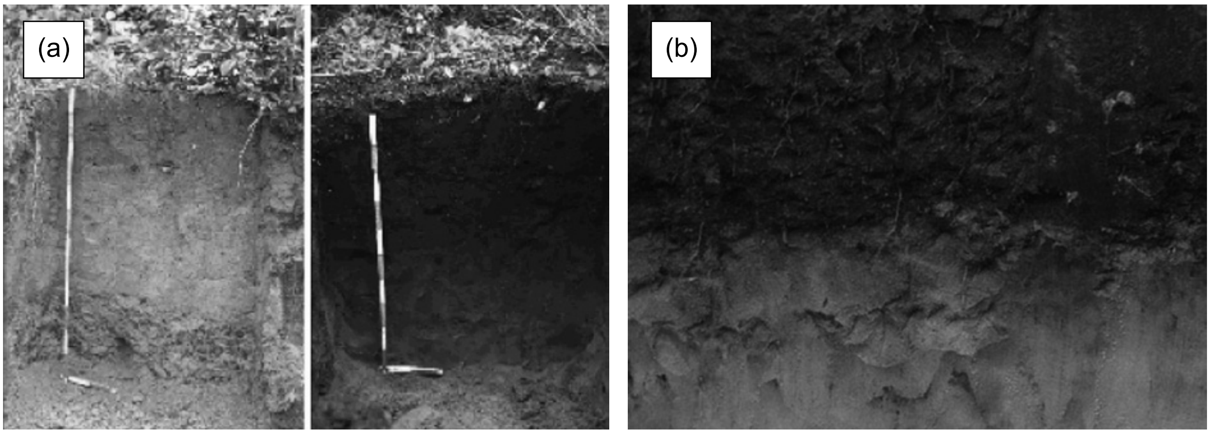

Figure 1. (a) Poor nutrient oxisols (left) and fertile Terra preta *transformed oxisols (right) (b) Close-up dark fertile soil.*

TABLE 1. SELECTED BIOCHAR PROPERTIES FROM DIFFERENT SOURCES OF BIOMASS

Types of char	Pyrolysis temperature (°C)	Biochar characteristics											References
		Fixed Carbon (wt. %)	Ash (wt. %)	Moisture (wt. %)	pH	Surface area ($m^2 g^{-1}$)	Elemental composition (% oven dry wt. basis)					Volatile matter (wt. %)	
							C	H	O	N	S		
Woodchip	465	90 – 98	9.3	7.2	11.0	0.19	71.2	3.0	11.4	0.20	N/A	N/A	Spokas and Reicosky (2009)
Rice husk	600	N/A	63	4.96	8.7	27.8	18.72	N/A	N/A	0.60	N/A	N/A	Masulili *et al.* (2010)
Hardwood (Pine bark)	450	62.8	7.9	N/A	8.6	N/A	75.2	2.74	24.7	N/A	0.02	29.3	Domingues *et al.* (2017)
Peanut hull	400	59	8.2	N/A	7.9	0.52	74.8	4.5	9.7	2.70	0.09	59	Novak *et al.* (2009)
Pecan shell	350	62	2.4	N/A	6.2	1.01	64.5	5.3	27.6	0.26	0.01	62	Novak *et al.* (2009)
Poultry litter	350	72	35.9	N/A	8.7	1.10	46.1	3.7	8.6	4.90	0.78	72	Novak *et al.* (2009)
Switch grass	250	89	2.6	N/A	5.4	0.40	55.3	6.0	35.6	0.43	0.05	89	Novak *et al.* (2009)
Corn stover	505	N/A	54.2	5.3	N/A	17.30	65.7	1.4	4.2	1.20	0.04	N/A	Spokas and Reicosky (2009)
Willow stem	500	N/A	7.9	N/A	N/A	1.55	69.2	3.6	11.8	1.53	0.04	3.8	Trakal *et al.* (2011), Kwapinski *et al.* (2010)
Manure	500	61.2	N/A	25	8.3	5.82	32.6	N/A	N/A	1.44	0.32	N/A	Stoyle (2011)
Palm kernel shell (PKS)	400	65.40	15.51	1.47	9.78	149.67	74.19	N/A	N/A	N/A	N/A	17.62	Kong *et al.* (2013)

Note: N/A - indicates that the data is not available.

Current awareness on the importance of sustainable practices has developed into a prominent trend such as recycling waste and converting biomass into valuable materials and energy. The abundant biomass generated each year in Malaysia leads to potential biochar production. Malaysia is the world's second largest producer and exporter of palm oil, contributing for about 94% of total biomass production. This includes empty fruit bunch (EFB), mesocarp fibre (MF), palm kernel shell

(PKS) and palm oil mill effluent (POME), which could be processed into value added products such as biodiesel, methane gas, bio-compost, plywood, animal feedstock, *etc*. Hence, biochar production could be another alternative to convert the abundant oil palm biomass into new value-added products using different conversion technologies.

Depending on the economic factors, different pyrolysis technologies are used to produce the maximum end products required (*Table 2* and *Figure 2*). The process involves a combination of time, heat and pressure exposure factors that can vary between processors, equipment and feedstock. Moderate temperature, high heating rate and short vapour residence time will maximise the production of liquid products, whereas high temperature, low heating rate and long vapour residence time will maximise the yield of syngas. Consequently, lower temperature with long vapour residence time will result in more char is produced per unit of biomass. Therefore, with regard to the use of biochar as a soil amendment, a slow pyrolysis process or known as carbonisation process is preferable because it maximises the yield of char compared to other pyrolysis processes.

TABLE 2. END PRODUCTS GENERATED BY DIFFERENT MODES OF PYROLYSIS PROCESS (dry wood basis)

Pyrolysis mode	Conditions	Process output (%)		
		Bio-oil	Biochar	Bio-gas
Fast	Moderate temperature (500°C) for short hot vapour residence time of 1 second	75	12	13
Intermediate	Moderate temperature (500°C) for moderate hot vapour residence time of 10 – 20 seconds	50	20	30
Slow (carbonisation)	Low temperature (400°C) for very long solid residence time	30	35	35
Gasification	High temperature (800°C) for long vapour residence time	5	10	85

Source: International Energy Agency (IEA) (2007).

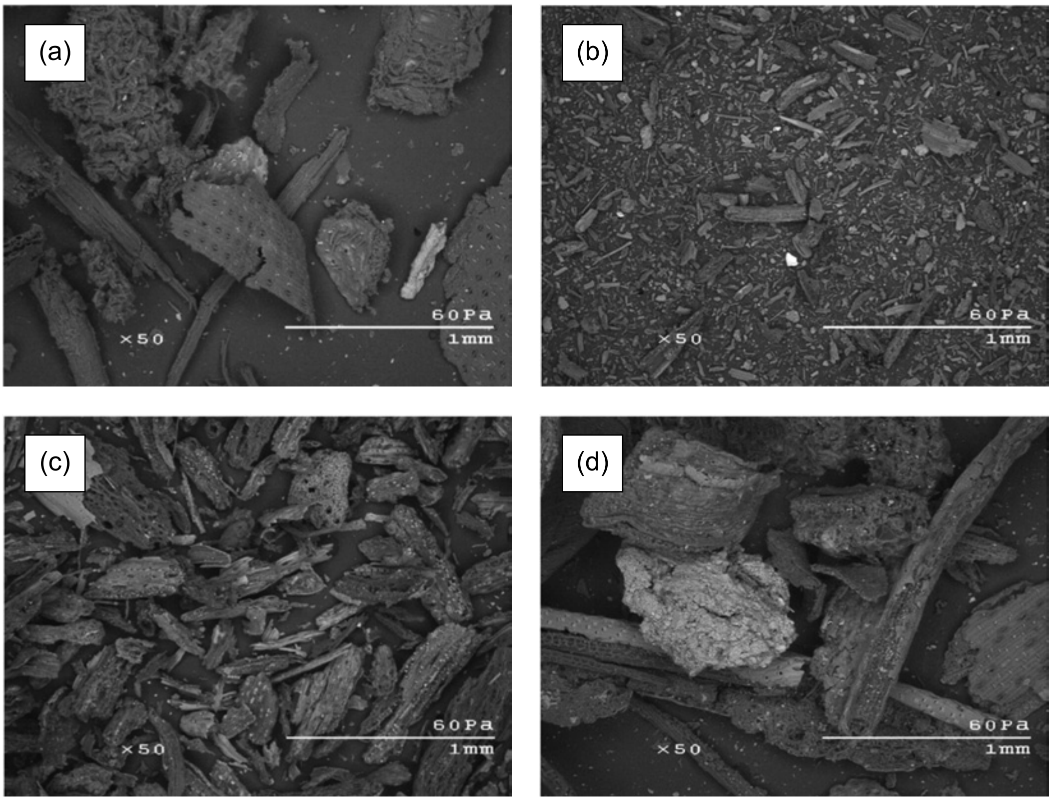

Figure 2. Scanning electron microscopy (SEM) images of (a) switchgrass feedstock, (b) slow pyrolysis biochar, (c) gasification and (d) fast pyrolysis biochar (pictures from Brewer et al.*, 2009) showed difference in porous structure that effects the quality of the pyrolysed products.*

Further research should be conducted to better understand the biochar properties of different biomass sources and various pyrolysis conditions. Environmental, economic, practical and energy balance aspects should be equally managed to meet the best solution for biomass utilisation, whilst completing in-depth research to narrow the current knowledge gap.

It is important to note that not all biochar is the same. The key chemical and physical properties of biochar are greatly affected by the type of biomass being heated and the conditions of the pyrolysis process. The different chars may look the same but the performance is completely different. Depending on the biomass used and the production processes, the application of biochars may lead to contradictory responses, either positive effects, adverse effects or no influence on certain soils and crop productivity (Chan and Xu, 2009; Jeffery *et al*., 2011; Schulz and Glaser, 2012; Alburquerque *et al*., 2014).

Why use Biochar?

a) **Climate Change Mitigation**

Current global warming issue has become world concern and much attention is given to reduce atmospheric GHG levels where the three main GHGs are Carbon Dioxide (CO_2), Nitrous Oxide (N_2O), and Methane (CH_4). CO_2 is the major contributor. In a long-term study on climatic scenarios (500 years), Weaver *et al*. (2007) found that at least 90% of global emissions reduction must be sustained before 2050 in order to keep the temperature rises below the 2.0ºC warming threshold, as supported by Meinshausen *et al*. (2009). Studies have shown that large scale application of biochar has the potential to mitigate global climate change by drawing down atmospheric GHG (greenhouse gas) concentrations (Sohi *et al*., 2010; Woolf *et al*., 2010). Recent researches have proven that biochar-enriched cultivated soils could reduce carbon dioxide (CO_2) and nitrous oxide (NO_2) emissions by 50%-80% (Singh *et al*., 2010, Yanai *et al*., 2007; Van Zwieten *et al*., 2009).

Biochar is also capable of storing carbon for long periods and producing renewable energy. It was indicated that up to 50% of the biomass carbon content remains in biochar through the production process, which is significantly higher compare to the remaining 20% of carbon in biomass after five to ten years of natural decay and the remaining 3% of carbon in ash after complete burning (Lehmann *et al*., 2006). The incubation experiment by Spokas and Reicosky (2009) showed that there was no mineralisation of biochar, which proved that the carbon material in biochar is fairly stable and is a permanent form of carbon sequestration.

In addition to high carbon content, biochar is also relatively inert and more persistent in soil than any other organic amendments. It is capable of sequestering carbon for long period from millennial to centennial timescales through studies of ancient anthropogenic activities (Lehmann *et al*., 2006). This enables soil to create a recalcitrant carbon pool that is carbon-negative, serving as a net withdrawal of atmospheric CO_2 stored in highly recalcitrant soil carbon stocks (Lehmann, 2007). Consequently, biochar has a significant opportunity as a potential carbon sink to restore soil organic carbon (SOC) greater than its natural potential.

b) **Soil Fertility**

Besides sequestering carbon, biochar application on soil is widely recognised for its great implication on soil fertility and plant productivity, essentially on nutrient efficiency. It was proven in improving soil properties such as CEC, pH, porosity, water holding capacity, leaching losses and increased crop productivities as well as microbial biomass and activities (Chan *et al*., 2007; Lehmann and Joseph, 2009; Dume *et al*., 2015).

Biochar is not a fertiliser, but it is a permanent investment in the soil as it hardly decomposes, is resistant to chemical and microbial degradation and is more persistent than any form of organic matter commonly applied to the soil, especially when buried. Biochar is used with fertiliser, not as a substitute, but as a high-efficiency delivery system due to its unique physical and chemical nature. Since biochar can retain up to six times its weight in water, basically biochar can store water and nutrients. Biochar attracts and holds moisture, nutrients and agrochemicals as well as retains nutrients like nitrogen and phosphorous. Biochar adsorbs and stores nutrients in fertilisers to make them easily available to plant roots. Furthermore, biochar can reduce soil acidity thus reduce the need for lime because it directly retains nutrients in soil through negative charges on its surfaces. These negative charges could also buffer the soil acidity. Generally, most agricultural soils have a soil pH below pH 7. Soil acidity characterised by low pH and high aluminium (Al) is a serious constraint on crop production, while liming is an expensive conventional remedy. Thus, it is necessary to increase the pH of the soil by introducing biochar to accommodate optimal crop growth. This improves fertiliser efficiency and allows growers to reduce fertiliser use while achieving high productivity, as reported in previous studies such as wheat (Yeboah *et al*., 2018; Abbas *et al*., 2017), rice paddy (Muhammad *et al*., 2017; Qin *et al*., 2016; Rosenani *et al*., 2013), maize (Faloye *et al*., 2017; Arif *et al*., 2017; Sarfraz *et al*., 2017), and other crops (Wang *et al.,* 2017; Amin *et al.,* 2017; Sarah *et al.,* 2013). Consequently, the reduction in the use of nitrogen fertilisers leads to a reduction in N_2O emissions. This suggests that biochar could be used as a useful measure to mitigate global warming by reducing GHGs as well as giving indirect benefits to the yield performance and nutrient supply.

One of the benefits of using biochar is the increase in cation exchange capacity (CEC) (Chan *et al.,* 2008; Agusalim *et al.,* 2010), which allows the soil to retain more nutrients, reduce nutrient leaching, moderate soil acidity, increase water retention, reduce soil bulk density, and provide habitat for beneficial soil microbes (Lehmann *et al.,* 2006). These benefits are provided by the unique properties of the high porosity observed in the scanning electron micrograph (*Figure 2*). Biochar has a large surface area and a high CEC, which enhances the sorption capacity of organic molecules and inorganic ions under a large number of reactive surfaces (Glaser *et al.,* 2002). A combination of moderate application rates of biochar could significantly improve soil quality and increase crop growth. Biochar may reduce fertiliser demand due to its ability to attract and maintain soil nutrients. As a result, the cost of fertilisation is minimised and the fertiliser remains in the soil for a longer period of time, not to mention the fact that biochar provides additional indirect climate change benefits by reducing fertiliser demand.

CONCLUSION

Biochar could be considered as a priceless investment in the soil as it holds precious properties. The benefits of the biochar obtained depend on their nature and the amount applied. Generally, biochar increases soil fertility by increasing soil pH, thereby reducing Al toxicity. Biochar reduces the leaching of critical nutrients and provides greater soil availability of nutrients. Hence, it stimulates plant growth, which then leads to an increase in consumption of carbon dioxide. By reducing the need for chemical fertilisers, biochar helps reduce emissions of greenhouse gases and mitigate climate change. However, there is still a lack of understanding of the important mechanisms and properties of biochar, which requires research, with a focus on diverge soil conditions and the environment. Furthermore, it is essential to differentiate between beneficial and detrimental biochar products to ensure that biochar is safe for agricultural purposes.

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