12. Biochar characteristics and application in the agriculture

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Abstract

Recently biochar gained importance as a way to deal with global climate change, by sequestering C into soils, but also as a soil amendment and bioremediation tool. Many studies have demonstrated the positive influence of biochar on soil quality and subsequently, plant growth, although the results are not consistent and climate seems to be the main reason for this inconsistency. Number of studies has been conducted to find out how biochar affect soil characteristic, fertilizers efficiency as well as soil microbiota. The main focus of this review is to discuss biochar features and it application in agricultural practices that could improve soil productivity and in consequence plant growth and development.

1. Introduction

Biochar, although not in the form we know today, has been used since centuries. The incorporation of charcoal into the soil to enhance soil quality has been an agricultural practice for thousands of years (Xu et al. 2012). Pre-Columbian people were combining charred residues of organic and inorganic wastes with the soils that are known today as Terra Preta - rich in organic matter and nutrients Amazonian soil. The oldest description of charcoal use in agriculture may be from the 17th century Encyclopedia of Agriculture by Yasusada Miyazaki, where he cited an even older textbook from China. We know from there that rice husk charcoal has been used as a soil amendment probably since the beginning of rice cultivation in Asia (Ogava and Okimori, 2010). Nowadays, the term "biochar" refers to a product of biomass pyrolysis, wherein plant-based materials are heated under anaerobic conditions to capture combustible gases. Originally, biochar production was associated with slow pyrolysis, characterized by a long time (more than 10 h) under relatively low temperature, typically around 400°C. More recently, there has been growing interest in biochar production through fast pyrolysis, where the organic materials are rapidly heated to 450-600°C (Xu et al. 2012). The reason why biochar gained public interest is mainly associated with its carbon sequestration ability. Biochar is a promising tool to reduce the atmospheric CO_2 concentration because it slows the return of photosynthetically fixed carbon to the atmosphere (Xu et al., 2012). The half-life of biochar in the soil is estimated to range from hundreds to thousands of years (Zimmerman 2010). Therefore, supplying the soil with biochar is a strategy for long-term carbon sequestration. Moreover, there is increasing interest in biochar as a soil amendment. Number of studies has demonstrated that biochar application can significantly improve crop productivity (Chan et al. 2007), improve soil conditions (Xu et al., 2012), and increase the efficiency of fertilizers (Asai et al., 2009), it can also be used in remediation processes (Chan et al., 2012). The main goal of this paper is to review the effect of biochar on soil properties and discuss it use in the agricultural practices.

2. Effect of biochar on soil characteristics

Numerous studies have demonstrated that biochar have a positive effect on soil quality. Biochar application can enhance organic matter content in soil what leads to increased soil fertility (Xu et al., 2012). Depending on the feedstock and the pyrolysis features used in biochar production, it can contain some nutrient but also due to its highly porous structure it can improve nutrient retention in the soil. Also, biochar can reduce soil acidity and increases soil electrical conductivity and cation exchange capacity (CEC), which results in higher nutrient availability (Laird et al. 2010). Some data show that biochar can reduce the availability of trace elements to plants. Namgay and coworkers (2010) found that concentrations of Cd, As and Cu in maize shoots significantly decreased after to the application of biochar, however; the uptake of heavy metals and their availability to the plant was varying, depending on the metal and the rate of biochar application. Glaser et al. (2002) reported that biochar application reduced aluminium toxicity to plant roots and soil microbiota. Considering the environmental issues associated with the contamination of arable soils with heavy metals biochar shows the potential to remediate cultivated soils. For example, Chan and coworkers (2012) provided some evidences showing that pine needle based biochar can be efficiently used in bioremediation of polycyclic aromatic hydrocarbons (PAHs) of contaminated soils. It was also shown that sewage-sludge biochar decreased the plant-available Zn, Ni, Cu and Pb, the mobile forms of Cu, Ni, Zn, Cd and Pb, as well as the risk of leaching of Cu, Zn, Ni and Cd. Freddo et al. (2012) reported that the concentrations of metals, metalloids and PAH in four plant-based biochars (rice straw, bamboo, redwood and maize) were lower than those reported as acceptable for sewage sludge and compost. Biochar has high total porosity (Fig. 1) therefore it can retain water in small pores and increase soil water holding capacity (Asai et al., 2009).

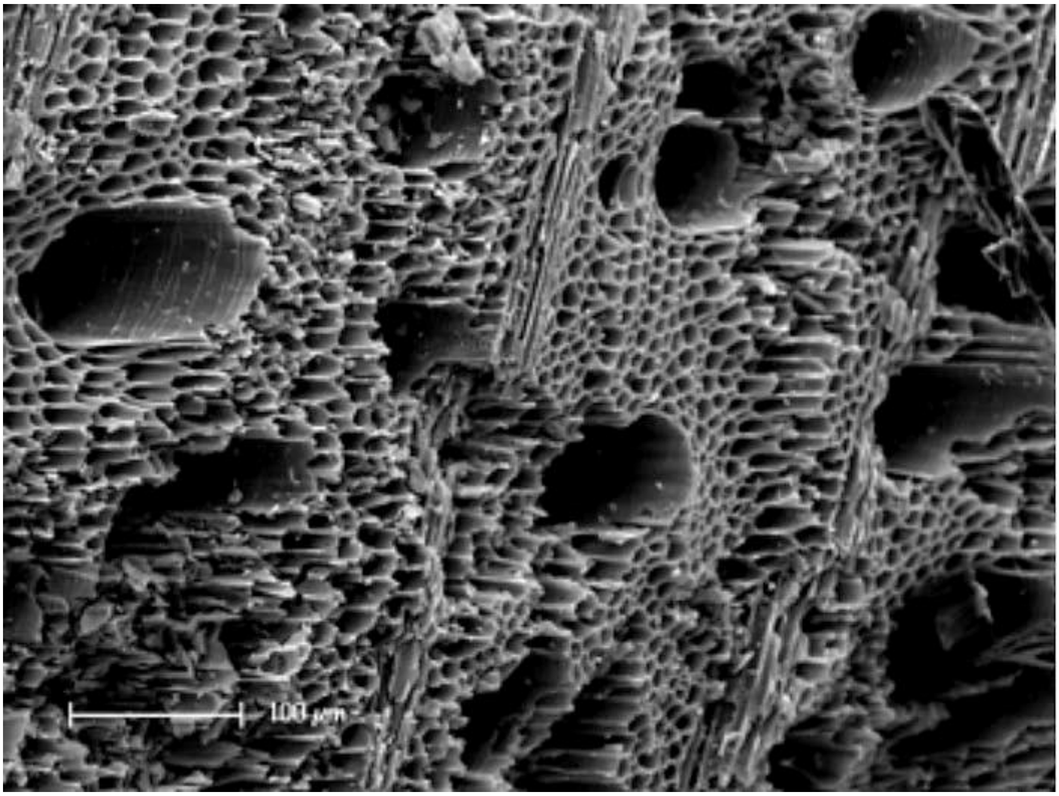

Figure 1. Biochar under a microscope, Brownsort, UK Biochar Research Centre.
From: http://www.nakanoassociates. com/biochar/

This may enhance water availability to crops and prevent form erosion. Some authors suggest that it can be an important tool to manage water in agricultural production, particularly under water stress conditions. For example, Artiola et al. (2012) report that biochar treatment significantly influenced Bermuda grass growth in a 1-month water-stress experiment where 100% of the control plants were killed. The survival rate of plant amended with 2 and 4% biochar were 50 and 100%, respectively.

3. Dual effect of biochar and mineral fertilizers

Some studies investigated a combined effect of mineral fertilizers and biochar. For example, Asai and coworkers (2009) reported that grain yield of rice was significantly higher after the application of biochar at a rate of 4 and 8 t ha^{-1} in the presence of N fertilizer. Pot trials with romaine lettuce showed that fresh weight was significantly higher after biochar application (at a rate of 2 and 4% w/w) compared to the control; similar effects were seen as a result of pre-treatment with concentrated fertilizer solution. The authors speculated that this increase might be due to the storage and release of fertilizer chemicals by biochar particles. Similarly, Hossain (2010) observed 20% higher yields of cherry tomatoes after application of biochar with fertilizer, compared to the fertilizer treatment alone. A pot trial was carried out to study the effect of biochar that had been produced from green waste on the yield of radish (Chan et al. 2007). Three rates of biochar (10, 50 and 100 t $ha^{–1}$) with and without additional N application (100 kg N $ha^{–1}$) were studied. In the absence of N fertilizer, application of biochar to the soil did not increase radish yield, even at the highest rate of 100 t ha^{-1}. However, a significant biochar and N fertilizer interaction was observed. For example, an additional increase in dry matter of radish, in the presence of N fertilizer, varied from 95% in the control to 266% in the 100 t $ha^{–1}$ biochar amended soils (Chan et al. 2007). Schulz and Glasern (2012) investigated the effect of biochar on soil quality and plant growth under greenhouse conditions. They showed that the addition of biochar to sand can increase plant growth. They observed a significant synergy when the biochar was combined with a mineral fertilizer or compost. These combinations have increased plant growth more than any increase due to pure biochar, compost or mineral fertilizer. Igarashi (1996) conducted a cultivation experiment for crops amended with rice husk charcoal. He applied charcoal with magnesium, phosphate, and lime, and rotated the soybean and maize crops. He reported that a charcoal application significantly increased plant growth, root nodulation and yield. The effect was sustained in the second crop of maize, and it continued up to the tenth crop rotation. He also reported that the growth and yield of maize treated with charcoal were greater than those of the control treatment, where only mineral fertilizers have been applied. All of the examples presented above highlight the capacity of biochar to improve the fertilizers efficiency in a crop production. Some authors (Asai et al. 2009) speculate that the fertilizer efficiency improvement might be associated with the capacity of biochar particles to retain and slowly release fertilizer chemicals. Others (Chan et al. 2007) attribute the fertilizer use efficiency to improved physical soil conditions or reduced fertilizer run-off as a result of biochar application. Although there is some speculation regarding the mechanism of this process, it is not completely understood, and there is still a need for further study.

4. Response of crop to the biochar application

There are a number of investigations that reported the beneficial influence of biochar on plant growth and development. Biochar can affect plant productivity in two ways: directly, as a result of its nutrient content and release characteristics; and indirectly, due to improved retention of nutrients, increase in soil pH, CEC, soil water retention and alteration of soil microbial populations and functions (Graber et al. 2010). Biochar significantly improves soil fertility; it influences soil structure, texture, particle size distribution, porosity, and density (Xu et al., 2012). Uzoma (2011) reported that biochar application at a rate of 15 and 20 t ha^{-1} increased maize grain yield by 150 and 98%, respectively, under sandy soil conditions. Graber (2010) found that number of nodes and canopy dry weight of tomatoes treated with biochar amendment (0, 1, and 3 wt %) were significantly higher than the control. In the same experiment, he showed that tomatoes treated with biochar had more buds and, in the end, more fruit. Although, he showed that fruit weight, whole plant yield, and single fruit weight were all significantly higher, he did not report differences between the two rates of biochar. Major et al. (2010) conducted a long-term (4 year) experiment in a Colombian savanna oxisol. Following the results, biochar application effect is most visible in the third and fourth years. Maize yield did not significantly increase in the first year, but in the second, third and fourth years after application of biochar at a rate of 20 t ha^{-1}, maize grain yield increased over the control (28, 30 and 140%, respectively). Likewise, in other long term study, Jones and coworkers (2012) reported no improvements in the growth of grass after first year from biochar application. However, in the second and third years after application, at rates of 25 and 50 t ha $^{-1}$, height and total dry biomass of grass, as well as foliar N, were significantly higher than the control. Plant growth can be directly affected by improved macro and micronutrient uptake. Chan et al. (2007) showed that the concentrations of P, K and Ca in radish tissue increased significantly after applying biochar at a rate of 50 and 100 t ha $^{-1}$. They reported that the increase in P and K contents in the radishes that grew in biochar treated soil was related to high concentrations of available P and exchangeable K present in the biochar. Also some studies have been conducted to investigate the effect of biochar on the germination process. Free at al. (2010) reported no significant effect of 5 different plant-based biochars on germination of maize in a paper towel assay. However, Solaiman et al. (2012) showed that biochar generally increased wheat seed germination at the lower application rates (10–50 t ha^{-1}) and decreased or had no effect at higher rates of application.

5. Biochar affect microbial communities

Soil microbial function and structure are beneficially affected when favorable conditions occur in the soil system. The soil microorganisms play a crucial role in soil structure and functioning. They are responsible for soil formation, ecosystem biogeochemistry, cycling of nutrients and degradation of plant residues and xenobiotics. The environmental factors which most significantly influence bacterial abundance, diversity and activity are moisture, temperature and pH (Wardle 1998). The pH of biochar depends on feedstock as well as type of pyrolysis applied in biochar production but generally biochar application might be a good way to adjust the soil pH. Because of the high WHC of biochar, it retains water and creates suitable and more stable habitats for bacteria. The biochar high WHC can be considered as suitable protection for microorganisms against desiccation. Biochar may retain moisture in the pore spaces that allow continued hydration of microorganisms in a drying soil. A number of research efforts in Japan, as well as recent investigations from the US, have shown that biochar supports the activity of many soil microorganisms important to agriculture. A recent review of biochar and its effect on soil biota (Lehmann et al. 2011) provides considerable evidences that application of biochar to the soil has significant effects on soil microbiota.

Biochar and its highly porous structure can provide a suitable habitat for many microorganisms (Fig 2.) by protecting them from predation and desiccation, providing carbon (C), energy and mineral nutrient.

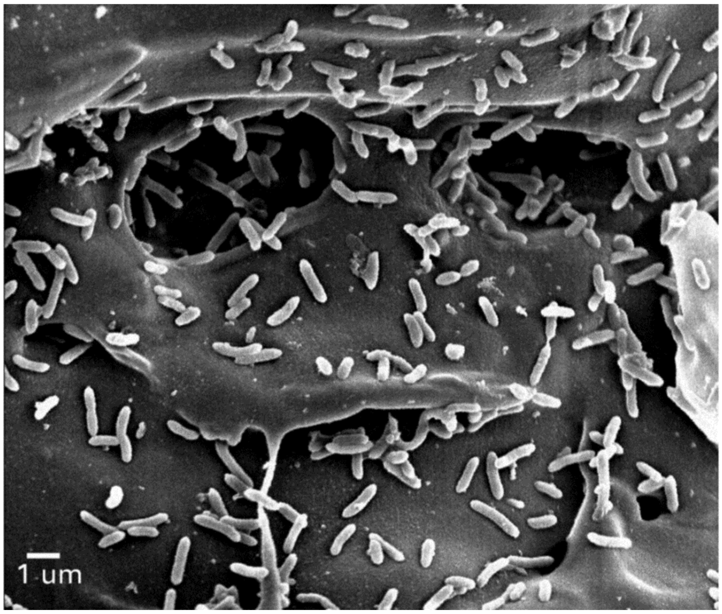

Figure 2. Scanning electron micrograph of the biochar with a syntrophic co-culture of *G. metallireducens* and *G. sulfurreducens*. From: Chen et al. 2014

The increase in bacterial abundance might be associated with sorption to the biochar surface, which prevents microorganisms from leaching and help to stabilize the population. Bacteria might be attached to biochar particles in different ways such as flocculation, adsorption on the surface, covalent bonding to carriers, cross-linking of cells or entrapment in a matrix (Lehmann et al., 2011). Biochar is also considered to be suitable protection for microorganisms against desiccation. Seasonal drying of soil leads to stress and, in effect, dormancy or mortality of some bacteria, with significant differences between gram-negative and gram-positive bacteria.

A number of studies provide evidence that biochar influences the composition of soil bacterial communities. It is commonly accepted that application of biochar leads to the changes of soil physicochemical properties and provides metabolically available sources of carbon (C), which may result in shifts in soil microbial community structure. Terminal restriction fragment length polymorphism (TRFLP) studies conducted by Anderson and colleagues (2011) show that biochar treatment enhanced the abundance of *Bradyhrizobiaceae* (~8%), *Hyphomicrobiacea* (~14%), *Streptosporangiaceae* (~6%) and *Thermomonosporaceae* (~8%). Some negative effects of biochar on the *Streptomycataceae* (~-11%) and *Micromonosporaceae* (~-8%) families were also observed. Increases in N_2-fixing rhizobia were reported in the rhizosphere whereas N_2-fixing *Frankiaceae* increased in both bulk and rhizosphere soil supplied with biochar. The authors suggest that biochar treatment potentially enhances the growth of bacteria involved in N cycling in the soil, particularly of those which may decrease the flux of N_2O. A similar study conducted by Kolton et al. (2011) shows that the genus most significantly affected by biochar application (3% wt/wt) was *Flavobacterium*. The total relative abundance of this group was 4.2% of all operational taxonomic units (OTUs) in the control treatment and 19.6% in biochar-amended soil. Simultaneously, there was a decrease in relative abundance from 71 to 47% for the genus *Proteobacteria*. The authors suggested that biochar-enriched soil led to important changes in the root-associated microbial community, characterized by induction of several chitin- and aromatic compound-degrading genera. Ameloot et al. (2013) hypothesised that the pyrolysis temperature in biochar production is a factor that might affect the microbial community. They found a correlation between Gram-negative bacteria and low temperature pyrolysis biochar. Furthermore, a high abundance of Gram-negative bacteria in a low 350°C biochar treatment and increases in Gram-positive bacteria in all types of biochar except that produced at 700°C was reported. Luo et al. (2013) provide the evidence that plant-based biochar pyrolyzed at low temperature (350°C) increases microbial colonization at high soil pH compared to biochar pyrolyzed at 700°C. They speculate that it might be because the availabilities of C, N and other nutrients were low in 700°C biochar, as most were lost during pyrolysis. They also speculate that lower colonization of the 700°C biochar might be because biochar produced at higher temperatures is characterized by fewer and finer pores, which results in fewer physical niches for bacteria. Abit et al. (2012) showed that biochar pyrolyzed at high temperature (700°C), and made out of pine chips, significantly reduced transport of *E. coli* through a sandy soil under water-saturated conditions when compared to the control, in column experiments. The authors explain that the difference between biochar types is due to differences in pore size distribution for biochars produced from different feedstocks. They suggest that incorporation of high temperature biochar made out of plant-based feedstocks to the soil might be a potential method for reducing microbial movement through soils, and it might be considered as a management practice for protecting shallow groundwater from pathogenic microorganisms.

6. Conclusion

Biochar became an important tool to mitigate the climate changes caused by anthropogenic activities. But as it is presented above biochar can also be successfully used in agricultural sector. The literature review presented above suggests that biochar is a material that significantly affects soil quality by changing its structure as well as chemical composition. It can be used in the water stress management and in the bioremediation processes, particularly in recovery of the soils contaminated with PAHs and heave metals. There are a growing number of evidences showing positive effect of biochar on plant growth and development; however this effect is strongly related to the climate and soil type. Also, biochar when applied together with mineral or organic fertilizers seems to significantly improve fertilizer efficiency and use by the plant. Finally, biochar was found to cause important changes in soil microbiota structure and function and it is believe to create favorable conditions for microorganisms.

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