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Review

Effect of biochar on soil structure – review

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Soil structure and organic matter are important indicators of soil quality. In the literature it states that there is a linear relation between soil structure and the organic matter. Mechanisms of formation and stabilization of aggregates have also been described in the literature, but it is evident that not every mechanism is applicable to various soil-climatic conditions. Recently, the modern but not the new term has become a biochar. It is anticipated that biochar is a significant source of C, and its application to the soil will improve the aggregation process in the soil. Lately we have been working in this area and we wanted to provide an overview of this issue through this review. The aim of this review was to collate and synthesize available information on soil structure and SOM. The emphasis of this review is on biochar and its combination with other organic and mineral fertilizers in relation to soil structure.

Keywords: biochar, soil organic matter, aggregation, aggregate stability

1 Introduction

Soil structure is a main soil property since it regulates soil water content, aeration and temperature of soils (Neira et al., 2015). Soil structure also positively influences plant germination and root growth. Therefore, assessing soil structure is an important issue in a determining soil quality (Ball and Munkholm, 2015).

Soil structure is usually defined as the spatial arrangement of soil particles and soil voids (i. e. soil pores), which may also be defined as the spatial distribution of soil properties. Soil structure includes the physical habitat of soil living organisms, and controls many important physical, chemical and biological soil functions and associated ecosystem services (Dexter, 1988). However, soil structure is more than only the physical arrangement of particles and pores and includes structural stability (i. e. the ability to resist endogenous factors or stresses) and structural resilience (i. e. the ability of recover upon stress removal) (Kay and Angers, 2001). Soil aggregation is responsible for soil structure and it is fundamental for soil to function as well as agricultural productivity.

Soil aggregates are secondary particles formed through the combination of mineral particles with organic and inorganic substances. Formation of soil aggregates as basic unit of soil structure is a function of physical forming forces (such as: inter and intramolecular forces, electrostatic, and gravitational forces) between soil particles (Grosbellet et al., 2011; Li and Fan, 2014; Hu et al., 2015) however, its stabilization is influenced by internal and external factors, and their interactions (Chenu and Cosentino, 2011; Paradelo et al., 2013; Šimanský et al., 2013; Jozefaciuk and Czachor, 2014; Šimanský and Bajčan, 2014).

Soil organic matter (SOM) also plays an important part in controlling soil quality and resilience because of the fundamental role it plays in determining a wide range of soil properties including buffering capacity, microbial biodiversity, water retention, and structural stabilization (Szombathová 1999; Šimanský et al., 2013; Šimanský and Polláková, 2016). For instance, humic substances (part of SOM) control buffering, cation exchange and water retention capacity of soils (Šimanský and Polláková, 2014), as well as the formation and stabilization of water-stable aggregates (Wang and Xing, 2005; Šimanský et al., 2013; Polláková et al., 2017). SOM is the major determinant and indicator of soil fertility and quality, and is closely related to soil productivity (Huang et al., 2007). Soil organic carbon (SOC) is an important agent responsible for binding soil mineral particles together creating an aggregate hierarchy (Oades and Waters, 1991). The dynamics of aggregate formation seem to be closely linked with soil organic carbon storage in soils (Golchin et al., 1997). Agro-technical operations and environmental changes modify the content and turnover of SOC. Intensive cultivation practices can stimulate

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biodegradation of the initially physically protected carbon in soil, and hence it could be responsible for the decrease of SOC (Norton et al., 2012; Khorramdel et al., 2013; Šimanský, 2017). Organic fertilizers, such as farmyard manure, compost, crop residues and others are often the most important sources of organic compounds in systems with continuous removal of organic crop residue. The last two decades have been characterized by a continuous decrease of livestock population, which had effect on decreasing availability of organic fertilizers and mainly production of perennial fodder for livestock (significant source of organic matter). At the same time, environmental and regulatory constraints have driven arable agriculture towards lower-input soil management, highlighting the need to maintain optimal soil function and a favourable balance of organic compounds in the soil. The same situation is in the Slovak republic. At present, from the point of view of the need for organic substances a 30–50% deficit is estimated (Green Report, 2014). From the point of view of sustainable land management, the balanced equilibrium of organic substances is essential and so new resources must be sought. One of the possible and innovative solutions can be the application of biochar.

Under these circumstances, the aim of this review is gather and synthesize available information on soil structure and SOM. The emphasis of this review is on biochar and its combination with other organic and mineral fertilizers in relation in soil structure.

2 Biochar as potential tool for improve agronomic practice

Biochar is a solid, carbon-rich product of thermal decomposition of organic matter, called pyrolysis, at a temperature higher than 400 °C and usually lower than 900 °C under conditions of oxygen deficit (Ahmad et al., 2014; Lehmann and Joseph, 2009). It is produced for environmental or agricultural application. Biochar is composed mainly of aromatic molecules that are not organised in ideally adherent layers (Hussain et al., 2016; Lehmann and Joseph, 2009). The structure and properties of biochar are in close relation to the conditions of pyrolysis (temperature and time of heat action). With increasing temperatures of pyrolysis, the content of carbon in biochar increases, while its content of hydrogen and oxygen decreases. Within the range from 400 to 700 °C an increase in pyrolysis temperature leads to higher aromaticity and hydrophobicity of biochar as well as higher volume of pores and specific surface area (Ahmad et al., 2014; Lehmann and Joseph, 2009). Various types of biomass can be used as feedstock for biochar production, such as wastes from wood processing, municipal wastes, sewage sludge, wastes from animal breeding and agricultural production (Hussain et al., 2016; Inyang et al., 2016; Stefaniuk and Oleszczuk, 2015; Usman et al., 2015; Zielińska et al., 2015).

The kind of matter used as feedstock has also an effect on properties of biochar. Therefore, is of the utmost necessity to consider the choosing of starting feedstock, according to the purpose to witch the biochar is to be used for. For example, biochar produced from animal manures usually has smaller specific surface area, than biochar which has been produced from wood and plant mass (Ahmad et al., 2014; Zielinska et al., 2015). Biochar has become the main focus of research in the recent past. The results of the experiments showed that application of biochar can be a sustainable way of improving physical, chemical, and biological properties. For example, up to now, there have been several studies published (Laghari et al., 2015; Agegnehu et al., 2016; Šimanský, 2016; Šimanský et al., 2016; Šimanský et al., 2017; Šimanský et al., 2017a) where authors concluded that biochar increased SOC in the soils due to its unique properties and structure which can potentially increase carbon sequestration (Lehmann and Joseph 2009; Šimanský et al., 2017a). In addition, the highly porous structure and large surface area of biochar (Figure 1) provide refuge for beneficial soil microorganisms such as mycorrhiza or bacteria (Pietikainen et al., 2000). This would be positive on microbial processes involved in nutrient cycling, decomposition of organic matter, and greenhouse gas emission (Pietikainen et al., 2000; Grossman et al., 2010; Deal et al., 2012). Among other aspects, it allows the carbon dioxide immobilization in soil and, in consequence, a reduction of its emission to the atmosphere (Conte, 2014; Horák and Šimanský, 2017). In experiments with biochars produced from biomass obtained from areas contaminated with heavy metals no elevated levels of any potentially toxic element (e.g. Cd or Pb) were noted (Evangelou et al., 2014). Another positive effect of the addition of biochar to soil to which various pesticides were applied was demonstrated by Oleszczuk et al. (2014). Biochar can also improve nutrient absorption, cation exchange capacity (Zwieten et al., 2010) sorptive parameters, mainly sorpion of soil organic matter (Šimanský et al., 2017) and increase of soil pH mainly in acidic soils (Karami et al., 2011; Horák et al., 2017). Rajkovich et al. (2012) refers that the biochar ash contains nutrients including base cations such as Ca and Mg causing a positive effect on the values of the degree of sorption complex saturation by base cations. Other studies found that abiotic changes after biochar addition take a short-time, with abiotic effects such as enhanced nitrogen or potassium availability disappearing after a single growth season, while the effects on functions such as plant productivity remained enhanced, suggesting that microbial changes rather than abiotic changes could

Table 1 Benefits of biochar application (Review)

Soil organic matter	Biochar is source of stabile organic matter and increase of C sequestration provide refuge for beneficial soil microorganisms such as mycrorrhiza or bacteria	Fischer and Glaser 2012; Pietikainen et al., 2000; Šimanský et al., 2016; Agegnehu et al.,2016; Horák and Šimanský, 2016
Greenhouse gasses	Reduce N_2O and CO_2	Horák et al., 2017; Horák and Šimanský, 2017;
Water retention characteristics	Improve soil matter regimes and available plant water content	Abel et al., 2013; Abrol et al., 2016; Novak et al., 2012
Cation exchange capacity	Improve sorptive properties of soils	Šimanský et al., 2017; Rajkovich et al., 2012
pH	Neutralization of acid soil	Karami et al., 2011; Horák, 2015; Horák et al., 2017
Porosity	Improve pore size distribution and pore continuity	Obia et al., 2016
Bulk density	Increase of bulk density	Ajayi and Horn, 2016; Mukherjee and Lal, 2013
Soil structure	Improve aggregation processes and increase of aggregate stability	Cornelissen et al., 2013; Herath et al., 2013; Šimanský, 2016

have led to the persistent effects of biochar addition (Mukherjee et al., 2014; Oram et al., 2014). Reviews of biochar effects on plant growth reported overall positive effects (Biederman and Harpole, 2013), but also show that there is considerable variability between studies, and that several studies showed negative effects (Liu et al., 2017; Hansen et al., 2017). In Table 1 are summarized some benefits of biochar application to the soils according to our available knowledge. Benefits of biochar as a soil amendment may vary with its properties, time after its application, and in relation to soil texture and mineralogy (Butman et al., 2015).

2.1 Effect of pure biochar on soil structure

Generally, there are several mechanisms of aggregation such as: hierarchical theory of aggregation (Edwards and Bremner, 1967), the concentric theory (Santos et al., 1997), the precipitation of hydroxides, oxides, phosphates and carbonates enhances aggregation (Bronick and Lal, 2005), cations also form bridges between clay and SOM particles resulting in aggregation (Jankowski, 2013) or it is possible that aggregates form through a combination of these processes (Bronick and Lal, 2005). All these mechanisms can be responsible for the formation and stabilization of soil structure after application of biochar to the soil. Applied biochar can be joined with mineral particles in the soil (Figure 2) or can be part of the soil aggregates (Figure 3 A, B). Biochar contains base cations (Rajkovich et al., 2012), which can be joined by the means of cationic bridges with clay and organic particles (Bronicki and Lal, 2005) and thus creating a favorable soil structure condition. Multivalent ions associated with biochar may have a positive effect through interactions with negative charged surface functional groups on SOM (e.g., R-COO–) and soil minerals (e.g., Al-O–, Si-O–) (Mukome et al., 2013). The bridging effects of multivalent ions, such as Fe^{3+} can enhance sorption of SOM to clay minerals (Feng et al., 2005). Other mechanism can be explained also through base cations, which can act as a bond between the mineral particles of the soil and the biochar particles (Lin et al., 2012 Joseph et al., 2013). Biochar in soil occurs not only as free particles, but these particles can also be connected with water-stable aggregates (Brodowski et al., 2006) but the effects on individual fractions of aggregates can differ, as indicated in study of Šimanský et al. (2016). For example, biochar (10 t ha^{-1}) applied without N fertilizer increased content of water-stable macro-aggregates (WSA_{ma}) in size fraction 5–2 mm, but at the same time decreased WSA_{ma} 0.5–0.25 mm content. Application of biochar (20 t ha^{-1}) had no remarkable influence on the content of WSA_{ma}. Adding lower amounts of biochar may thus be more beneficial for soil aggregation than higher rates of biochar addition. Secondly, aggregation effects mainly on lower size of aggregates depend on biochar particles. For example, conversion to WSA_{ma} 0.5–0.25 mm might therefore be difficult and could occur only after some time. According to Piccolo and Mbagwu (1999) hydrophobic components of organic matter contribute more to soil aggregate stability than hydrophilic components. Through, it´s highly aromatic C structure, biochar can improve aggregation by helping to bind native SOM, enhancing the resistance of soil aggregates to water and making aggregates more resistant to physical disturbance (e.g., wet-dry cycles). Biochar can also influence soil aggregation by change of the ionic composition of the soil solution. The surface of biochar particles after oxidation may by rich for hydroxyl and carboxylic groups which are able to adsorb soil particles and clays and form macro-aggregates

(Jien and Wang, 2013) however, this process is tedious and it takes long time. Several mechanisms may be involved in the biochar-induced improvements in soil aggregation. Previous research indicates that biochar can influence soil aggregation by changes of soil pH and enhance aromaticity of soil organic C pool (Chan et al., 2008; Novak et al., 2009). Higher soil pH can increase the flocculation of clay particles (Haynes and Naidu, 1998), it facilitating the formation of water-stable aggregates (Boix-Fayos et al., 2001). A slight increase of soil pH due to biochar amendment can benefit soil aggregation (Kookana et al., 2011). Biochar can also significantly affect on soil microbial communities by providing feedstock for production of extracellular polymeric substances that there are as cementing agents for soil aggregates (Le Guillou et al., 2012). Earthworms can affect aggregate stability in soil (1) mechanical bondings between soil and biochar particles, (2) mechanism in increase of fungi which is induced of excreted casts. The fungal hyphae are considered to be a significant stabilizing factors for soil aggregates because it connects soil particles by production of polysaccharides (Rahman et al., 2017). Soil bacteria are almost activated on joining of smaller

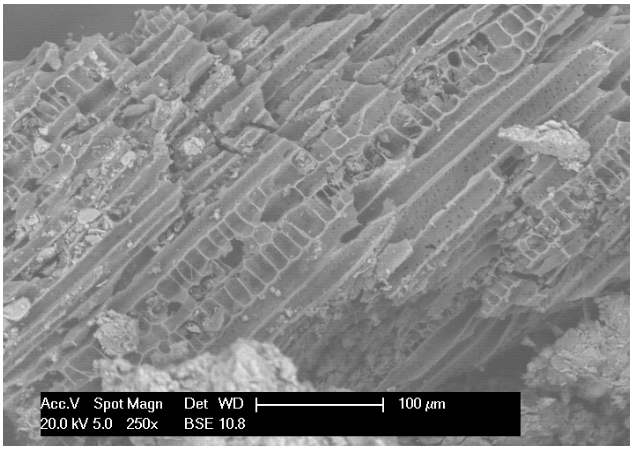

Figure 1 Porous structure and large surface area of biochar (Authors)

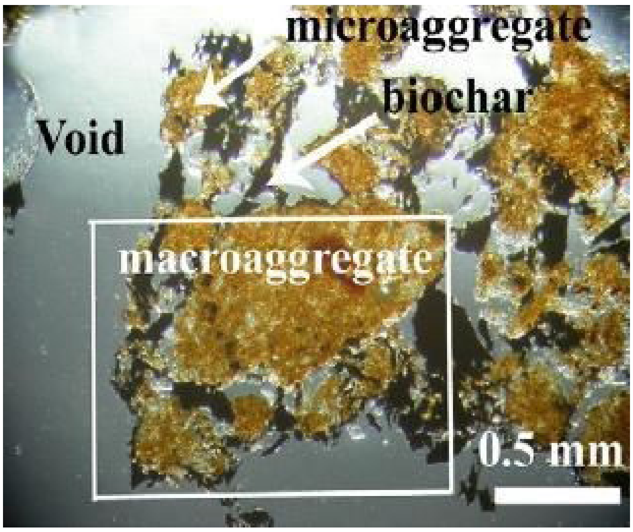

Figure 2 Biochar can join mineral particles in the soil (Jien and Wang, 2013)

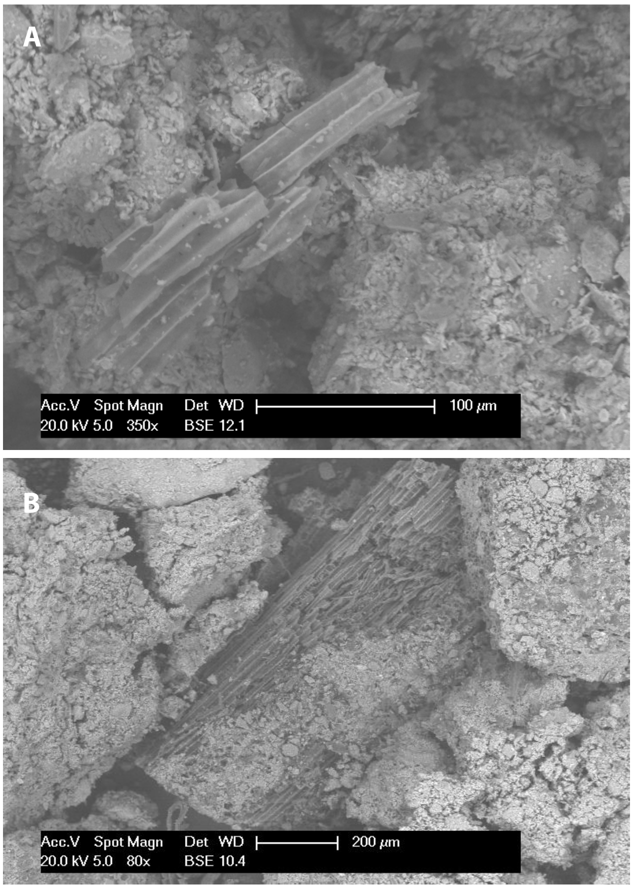

Figure 3 Biochar incorporated into soil aggregate (Authors)

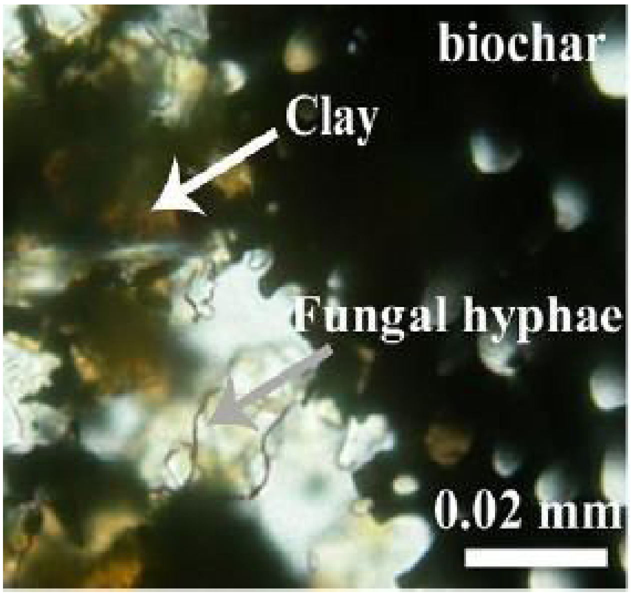

Figure 4 Fungal hyphae improve aggregation between biochar and soil particles (Jien and Wang, 2013)

particles, while soil fungi are active upon connecting to larger particles (Figure 4).

The different effects might be a result of differences in the biochar reactivity (i.e., amount of reactive functional groups) that strongly depends on production conditions and feedstock (Keiluweit et al., 2010) but also a length of time (length of contact between biochar and soil particles). Significant effect of biochar on soil aggregation is associated with applied doses of biochar and size particles of biochar (Šimanský et al., 2016).

2.2 Effect of biochar combined with other organic or mineral fertilizers on soil structure

One of the problems with the use of organic residues such as composts, manures, crop residues, which are added to soil for C sequestration is their relatively fast rate of degradation, leading to the release of carbon-dioxide, thereby becoming a source for greenhouse gas emission. Therefore, there have been increasing interests in the conversion of organic residues into biochars in order to reduce the rate of decomposition, which enhances C sequestration in soils (Kookana et al., 2011). Biochar is emerging as an attractive option to improve the efficiency of fertilizer use (Zhang et al., 2010). Biochar, due to its mostly inert nature, is often applied to soils in conjunction with organic or mineral fertilizers (Asai et al., 2009; Laird et al., 2010). The reasons for higher aggregate stability could be explained by the application of higher rates of biochar together with nitrogen fertilizer. Application of fertilizers generally improve soil aggregation (Munkholm et al., 2002). Added nitrogen to the soil can increase the processes of biochar mineralization and the result can be also a higher aggregation (Bronic and Lal, 2005; Šimanský et al., 2016). Despite beneficial properties of biochar, in most intensively managed agro-ecosystems, biochar is usually applied in combination with chemical fertilizers due to its low N, P, and K contents (Lima and Marshall 2005; Chan et al., 2007). In study of Šimanský et al. (2016), the application of N fertilizer together with biochar had a positive effect on the incorporation of biochar into the larger aggregates. In case of B20N80 treatment (20 t biochar ha^{-1} and 80 kg N ha^{-1}), the values of WSA_{ma} in the size fractions 3–2 mm (75%) and 5–3 mm (149%) were higher, while the size fraction of 0.5–0.25 mm (27%) was lower than in B20N0 (20 t biochar ha^{-1} + no nitrogen). Considerably lower content of WSA_{ma} 5–2 mm was observed in B10N80 (10 t biochar ha^{-1} and 80 kg N ha^{-1}). Adding nitrogen to the soil can improve microbial activity (Lehmann et al., 2011), increase the intensity of the biochar mineralization processes and increase CEC and active surface area (Yeboah et al., 2009), which results in higher aggregation (Bronic and Lal, 2005). The reduction of the addition of the chemical fertilizer rate may depend on the surface oxidation of biochar through changes in pH, oxidative state, or microbial community structure (Liu et al., 2011). According to Ma et al. (2015) both the NPK fertilizer + maize straw and NPK + biochar treatment significantly increased the relative proportion of macro-aggregates (>2 mm) and the mean weight diameter, and reduced the relative proportion of micro-aggregates (<0.25 mm). The higher proportion of macro-aggregates was recorded in the NPK + biochar treatment; the proportion of >2 mm aggregates was 15% higher than in the NPK + straw treatments, respectively. Compared with the NPK treatment, both the NPK + maize straw and NPK + biochar treatments significantly improved the stability of soil aggregates. When biochar is applied together with green manure as e.g. *Tithonia diversifolia*, there is likely a higher amount of microbial community and their activity (Li et al., 2012) and at the same production of metabolites which, through a variety of bonding mechanisms, can contribute to aggregate build. On the other hand, the biochar produced with the combination of wood and straw had no effect on aggregate stability (Annabi et al., 2007). The combined application of biochar and slurry might be a way to increase the biochar reactivity and, consequently, the ability to form macro-aggregates because slurry contains reactive compounds such as organic acids (Provenzano et al., 2014). The combined application of biochar and slurry led to lower aggregate yields than the solitary application of slurry. However, interactions between biochar and mineral soil particles were already found shortly after the application in both the incubations and in the field trial, leading to an increase of aggregate-occluded and thus protected soil organic carbon, almost in combination with a slurry application (Helfrich et al., 2008; Le Guillou et al., 2012).

3 Conclusion

In recent years, research activity on the use of biochars in soils has been increased and this trend is likely to continue over the next years due to the numerous potential benefits which we mentioned in this review and on the other hand risks associated with the use of biochars alone or in combination with other organic or mineral fertilizers. Due to the inherent complexity of biochar, soil properties, and cropping system, the effect of biochar on soil aggregate may be very different and the knowledge gap with respect to biochar follow from various crop residue feedstocks on dynamic of SOC and soil aggregate stability is very large. Soil aggregate stability can be changed based on biochar amendment in some cases depending on soil and biochar type but also a length of time (length of contact between biochar and soil particles) as well as applied doses of biochar and size particles of biochar. It is still unclear how combining biochar with N fertilization affects soil structure, but the major responsible factors include particle-size distribution of studied soils application rate of biochar, time after biochar application.

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