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Some Effects of Biochar on Soil Microorganisms: A review article

A bioszén néhány hatása a talaj mikroorganizmusaira: áttekintő cikk

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Abstract: Using biochar as a soil amendment is suggested to be a win/win technology for enhancing physical and chemical soil properties, yet little is known about the effects of biochar on soil microorganisms. This review underscores twofold of soil microbiological features studied in short-term experiments. 1) microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and basal soil respiration (BSR). 2) β-glucosidase, dehydrogenase, and urease enzymes activities under different doses and types of biochar and soil. MBC, MBN, BSR β-glucosidase, dehydrogenase, and urease and enzymes activities responded to biochar application depending on biochar dose, type, inorganic fertilizer application, soil type and cultivated plant. MBC, MBN, and BSR increased linearly after gradual amendments of cotton straw biochar while just low doses were effective for raising β-glucosidase, and dehydrogenase activities. Only high doses of wheat and corn straw biochar were effective to increase MBC while linear increments were witnessed under swine manure biochar. Across all biochar types, MBN showed an upward trend with increasing biochar rates hitting the heyday at the highest doses. On the other side, wheat straw and apple branch biochar caused gradual increments in β-glucosidase and urease activity with NPK (nitrogen-phosphorous-potassium) amendment after 72 months.

***Keywords**: biochar, microbial biomass carbon, microbial biomass nitrogen, basal soil respiration, enzyme activity*

Összefoglalás: A bioszén talajjavítóként való felhasználása a talaj fizikai és kémiai tulajdonságainak javítására szolgáló win/win technológia, ugyanakkor keveset tudunk a bioszén talaj mikroorganizmusokra gyakorolt hatásairól. Ez az áttekintés a talaj mikrobiológiai jellemzőinek változásaira hívja fel a figyelmet, melyek a következők:1) mikrobiális biomassza szén (MBC), mikrobiális biomassza nitrogén (MBN) és bazális talajlégzés (BSR) alakulása. 2) A β-glükozidáz, dehidrogenáz és ureáz enzimek aktivitása különböző dózisokban és eltérő típusú bioszenekben. Az MBC, MBN, BSR β-glükozidáz, dehidrogenáz, ureáz enzimek aktivitása reagált a bioszén kijuttatására a dózistól, a bioszén típustól, a szervetlen műtrágya kijuttatásától és a termesztett növénytől függően. Az MBC, MBN és BSR lineárisan nőtt a gyapotszalma bioszén kijuttatást követően, még az alacsony dózisok is hatásosak voltak a β-glükozidáz és a dehidrogenáz aktivitás növelésére. Csak nagy dózisú búza és kukorica szalmából származó bioszén hatékonyan növelte az MBC-t, míg a sertéstrágyából nyert bioszén esetében ez az emelkedés lineáris volt. Az MBN az összes bioszén típust tekintve emelkedő tendenciát mutatott, és a bioszén arányának növekedése a legmagasabb dózisok mellett volt a legnagyobb. A búzaszalma alkalmazása három időszakban (48, 60 és 72 hónap) jelentősen csökkentette az ureáz aktivitást, míg a BSR csak a leghosszabb távú megfigyelésben csökkent nagyobb mértékben. A másik oldalon a búzaszalma bioszén a β-glükozidáz és az ureáz aktivitás fokozatos növekedését okozta NPK (nitrogén-foszfor-kálium) adagolásnál 72 hónappal a kijuttatás után.

Kulcsszavak: *bioszén, mikrobiális biomassza szén, mikrobiális biomassza nitrogén, bazális talajlégzés, enzimaktivitás.*

1 Introduction

Biochar is a solid carbonaceous residue made by burning biomass under oxygen-free to oxygen-deficient conditions. Wood chips, crop residues, nut shells, seed mill screenings, algae, animal manure, and sewage sludge are some of the many feedstocks used in biochar production. It is highly resistant to decomposition when applied to soil, and its residence time ranges from tens of years to millennia (Preston and Schmidt, 2006; Verheijen et al., 2010). This reuse of what would otherwise be agricultural waste has become an emerging technology for sustainable soil management to add biomass as an organic amendment (Cernansky, 2015). Its application can improve soil fertility and plant productivity (Jeffery et al., 2014; Lehmann, 2007), as well as improve soil porosity (Omondi et al., 2016). Compared to its effect on soil characteristics and fertility and eutrophication management (Jia et al., 2018), the effects of biochar on the microbial communities of soil have been less thoroughly assessed (Lehmann et al., 2011, 2015).

Biochar may interact with soil microorganisms either directly, by being degraded and utilized, or indirectly, by improving soil properties and habitat conditions (Ameloot et al., 2013) as well as by indirectly i) serving as a refuge habitat, which protects microbes against grazers and predators, ii) improving physical soil properties, e.g., water holding capacity, bulk density, and aeration, and iii) modifying chemical soil properties, e.g. pH, cation exchange capacity (CEC), nutrient retention and sorption of soil organic matter (Lehmann et al., 2011). Overall effects of biochar on soil bacterial diversity and community structure depend on biochar type, pyrolysis temperature, experiment type, precipitation conditions (Wang et al., 2023), soil type, and agricultural management, such as crop type and planting duration (Abujabhah et al., 2016; Dai et al., 2016; Herrmann et al., 2019; Liu et al., 2018; Yu et al., 2018).

This review examines two groups of soil microbiological aspects affected by biochar: First, MBC MBN, BSR. Second, β-glucosidase, dehydrogenase, and urease enzymes activities.

2 Biochar effects on Soil Microorganisms

2.1 MBC, MBN and BSR

MBC, MBN, BSR, and enzyme activities are commonly determined biochemical properties due to primary regulators of many soil processes, thus considered important indicators of soil quality (Shao et al., 2008).

MBC increased across all soil types except the sandy loam soil with a low OC content (1%). MBC in calcaric Fluvisol and fluvo-aquic soils has markedly increased with (swine-manure and cotton straw) biochar rates increment while wheat and corn straw biochar revealed significant increases in sandy loam and fluvo-aquic soil MBC at the highest rates of amendment generally. On the other hand, a short-term experiment (2 years) showed a significant reduction in MBC after the addition of gradual biochar doses in alkaline sandy loam soil with only 1% of OC growing wheat with no fertilizer. A significant increase of MBC could be seen at 5 t ha^{-1} when mash bean was sown in the same soil with no fertilizer while a different pattern was clear after introducing the fertilizer showing a marked decline only at 5 t ha^{-1}.

Generally, MBN showed an upward trend with increasing biochar rates hitting the heyday at the highest amendments across all examined soil types regardless of (sandy loam soil growing wheat under NPK fertilizer) which experienced a significant reduction compared to the control (Azeem et al., 2019). MBC was initially higher but decreased in the second year of biochar amendment (both with and without fertilizer) which may be attributed to the positive priming effect at the start of the experiment and DOC (dissolved organic carbon) significant reduction to 0.45 g kg^{-1} after the second year (Azeem et al., 2019). However, some other studies showed a significant increase in MBC under a low biochar application rate (<2%) (Prayogo et al., 2014; Mingkui and Walelign., 2015). No significant change in MBC was also observed under a low biochar addition ratio (<8%) in temperate soil (Anders et al., 2013). An explanation for MBC changes in response to additions of biochar includes enhanced availability of soil nutrients (i.e P, Ca, and K), adsorption of toxic compounds, and improved soil water and pH status. All these changes have an impact on the activity of soil microorganisms (Lehmann et al., 2011).

BSR showed an upward trend across all the studied soil types except in the sandy loam soil amended with wheat straw biochar. BSR values after the amendment of cotton and corn straw biochar to calcaric Fluvisol and fluvo-aquic soils showed significant increments but regarding the corn straw biochar application there were not any significant differences among the doses. However, sandy loam soil BSR responded after the amendment of sewage sludge biochar with rising at the highest dose only whereas wheat straw biochar negatively affected sandy loam soil BSR at the highest rate only.

Higher respiration rates for soils treated with biochar could have been mediated by an improved soil structure, leading to enhance both aeration and microbial activity (Busscher et al., 2010). The reduction in BSR could be linked to the improved efficiency in carbon use because of the co-location of microorganisms and carbon on biochar surfaces, which reduces the need for enzyme production (Lehmann et al., 2011).

Table 1 Soil microbial biomass carbon MBC, MBN Soil microbial biomass nitrogen and BSR under different biochar feedstock and rates

Feedstock type	**Pt**	**Soil type pH**	**OC g kg $^{-1}$**	**Plant**	**Application rate**	**MBC**	**MBN**	**BSR**	**References**
						mg kg^{-1}	**mg kg^{-1}**	**mg CO_2eC kg^{-1} soil**	
Cotton straw	450	Calcaric	16.2	Cotton	With NPK				(Liao et al., 2016)
		Fluvisol			0	367^{b}	34.1^{b}	15.6^{b}	
		7.8			2.25	427^{ab}	33.4^{b}	16.1^{ab}	
					4.5 t ha^{-1}	485^{a}	52.5^{a}	17.7^{a}	
Wheat straw	350–550 2-mm	Sandy loam	20.1	Rice paddy	No fertilizer				(Chen et al., 2016)
		18 months			0	558.0	30.63	32.92	
		5.92			20	579.4	39.46	29	
					40 t ha^{-1}	620.8	43.51	25.63	
						LSD=			
						58.22			
							LSD=	LSD=	
							11.7	6.06	

Swine-manure	350	Laterite	2.84	Tea	No fertilizer	62.40^{a}	8.34^{a}	NA	(Jiang et al., 2021)
	9 months	5.4			0	65.98^{b}	9.36^{b}	NA	
					0.5	80.63^{c}	10.33^{b}	NA	
					1	85.14^{d}	11.12^{c}	NA	
					2%			NA	
Sewage sludge	600	Sandy loam	8.87	No plant	0	1055^{a}		1631^{a}	(Paz-Ferreiro et al., 2011)
	70 days	6.50			Sl4	1292^{a}		1197^{c}	
					Sl8	599^{b}		1364^{b}	
					B4	1375^{a}		1382^{b}	
					B8%	1404^{a}		808d	
Sugarcane bagasse	350	Sandy loam	1	Mash bean	No fertilizer			NA	(Azeem et al., 2019)
	2 years	8.5			0	426^{b}	20.2^{b}	NA	
					5	440^{ab}	23.6^{ab}	NA	
					10 t ha $^{-1}$	432^{b}	25.5^{ab}	NA	
					NPK				
					Fertilizer				
					0	462^{a}	24.6^{ab}	n	

					5	450^{ab}	23.1^{ab}		
					10 t ha $^{-1}$	460^{a}	26^{a}		
Sugarcane bagasse	350	Sandy loam	1	Wheat	No fertilizer				(Azeem et al., 2019)
	2 years	8.5			0	430^{a}	18.5^{ab}	NA	
					5	401^{b}	21.4^{ab}	NA	
					10	377^{cd}	21.7^{ab}	NA	
					NPK				
					Fertilizer				
					0	444^{a}	26.3^{a}	NA	
					5	373^{d}	19.7^{ab}	NA	
					10 t ha $^{-1}$	394^{bc}	19.7^{b}	NA	
Corn straw	500	fluvo-aquic	9.51	No plant	250 kg N ha$_{-}^{1}$				(Xu et al., 2016)
	<1 mm	8.1		150 days	0	75.12^{b}	8.24^{b}	70.68^{b}	
					2	79.45^{ab}	8.56^{ab}	89.19^{a}	
					4	75.31^{b}	8.59^{ab}	96.86^{a}	
					8%	83.27^{a}	8.86^{a}	94.53^{a}	

Pt: Pyrolysis temperature. (Liao et al., 2016) NPK: s 300 kg N ha-1 urea, Triple super phosphate (105 kg P_2O_5 *ha*$^{-1}$*) and potassium sulfate (60 kg* K_2O *ha*$^{-1}$*).*

2.2.β-glucosidase, Dehydrogenase and Urease Enzyme Activity

Soil enzymes have different roles such as the C-degrading enzymes include α-glucosidase, β-cellobiosidase, and β-glucosidase (Chen et al., 2016). In addition to the dehydrogenase activity that has been used as a parameter for the evaluation of the degree of recovery of degraded soils (Gil-Sotres et al., 2005). Urease and phosphatase are two important enzymes involved in the nitrogen and phosphorus cycles, respectively (Pascual et al., 1998). Urease is involved in the hydrolysis of urea-type substrates and its origin is basically microbial and its activity is extracellular (Bremner and *Mulvaney*, 1978). This enzyme may form stable complexes (urease–humus) (Nannipieri et al., 1980).

β-glucosidase enzyme activity decreased almost in all studied soil types and carbon contents except in silty clay soil amended with apple branch biochar accompanied by urea. β-glucosidase enzyme activity of cotton straw with NPK and apple branch biochar with urea has been increased importantly starting from the lowest dose but with no important differences among doses for cotton straw biochar. On the other side, β-glucosidase enzyme activity in sandy loam and silty clay soils declined markedly under gradual doses of wheat straw, sewage sludge, and apple branch biochar without urea amendment. Volatile compounds in biochar produced at low temperatures (350-500 °C) stimulate enzymatic activity, including dehydrogenase activity and β-glucosidase activity (Ameloot et al., 2013; Bailey et al., 2011). While reductions in β-glucosidase activity were reported under the amendment of fast-pyrolysis biochar produced from switchgrass (Bailey et al., 2011). Lammirato et al. (2011) also found that biochar addition caused a decrease in the rate of the reaction catalyzed by β- glucosidase.

The dehydrogenase activity decreased under poultry litter and wheat straw amendments to loamy sand soil, as well as in sandy loam soil amended with sugarcane bagasse but without fertilizer. On the other hand, dehydrogenase activity increased in sandy loam soils after the addition of sewage sludge and sugarcane bagasse biochar with no fertilizer. Although, no significant changes in dose variations in biochar additions of wheat straw and sugarcane bagasse growing rice and mash bean were observed, the dehydrogenase activity increased significantly after the addition of wheat straw and sugarcane bagasse growing rice and mash bean (without fertilizer) but among the treatments, the variations were not significant. But for wheat straw biochar amendment with NPK, after 72 months in a loamy sand soil growing winter rye, dehydrogenase activity rose markedly with the increasing dose ones. On the same grounds, its activity grew significantly only after the usage of 8% (the highest rate) of sewage sludge biochar. However, the application of poultry litter biochar in a loamy sand soil growing pasture grass caused a significant drop compared to the control, but not among the biochar rates. The previous results are consistent with Demisie et al. (2014) who revealed that the highest dehydrogenase activity was measured in both oak wood and bamboo biochar pyrolyzed at 600 °C at the lowest rate of 0.5% in a clay loam soil. Similarly, Irfan et al. (2019) indicated this improvement under biochar application rate of 1% C (w/w).

Urease enzyme activity showed a downward trend across all soil types except for loamy sand soil treated with poultry litter biochar. Urease activity decreased significantly in sandy loam soil with increasing biochar rates of sugarcane bagasse biochar without NPK. A similar trend could be seen in silty clay soil in the treatment without urea and apple branch biochar but without significant variations between 1-4% amendment rates. When NPK was introduced to the Sugarcane bagasse biochar for mash bean plant, urease activity lessened significantly at 5 t ha^{-1}. But under urea usage and apple branch biochar, it witnessed a significant fluctuation starting with an increment at 2% followed by a drop at 4%.

Urease activity in loamy sand soil for both biochar types (poultry litter and wheat straw biochar after 72 months) increased gradually when biochar doses were used compared to the use of NPK treatment only; while by comparing the three periods for wheat straw biochar use

(48, 60, and 72 months) it has decreased significantly. Woody biochar amendment to silt loam also caused a considerable increase in urease activity at the dose of 22 Mg ha $^{-1}$.

Biochar produced at a pyrolysis temperature of 350–550 °C with a pH of > 10 and C/N ratio of < 50 increased the urease activity to a greater extent than those produced at other pyrolysis conditions (Pokharel et al., 2020). However, the activities of N and P enzymes were related to the application rate and biochar type. The addition of 10 mg kg^{-1} biochar stimulated the activities of alkaline phosphatase and urease (Huang et al., 2017). On the other side, the reduction in urease activity could have been attributable to the decline in soil properties due to monoculture cropping of rye and also to the effect of biochar aging (Futa et al., 2020). Gul et al. (2015) detected changes in biochar characteristics due to its aging in soil, in particular on account of its oxidation and the accumulation of H^+ from the soil solution.

Table 2 β-glucosidase, dehydrogenase and urease activity under different rates and feedstock of biochar

Feedstock type	**Soil type**	**OC** **g kg $^{-1}$**	**Pt**	**Plant**	**Application rate**	**β-glucosidase**	**Dehydrogenase activity**	**Urease activity**	**References**
						mg p-nitrophenyl kg^{-1} soil h^{-1})	**[mg TPF kg^{-1} h^{-1}]**	**[mg N__NH4^{+} kg^{-1} h^{-1}]**	
Poultry litter	Loamy sand	8.87	300	Pasture grass mix	0	NA	0.74^{ab}	8.61^{a}	(Mierzwa-Hersztek et al., 2016)
					NPK	NA	0.63^{a}	4.78^{c}	
					PL	NA	0.88^{b}	12.4^{b}	
					2.25+	NA	0.70^{a}	8.38^{a}	
					5 t ha $^{-1}$+	NA	0.72^{a}	11.1^{b}	
Wheat straw	Loamy sand	5.95	650	Winter rye	With NPK				(Futa et al., 2020)
				72 months	0	NA	1.25^{a}	2.05^{a}	
					10	NA	2.80^{b}	2.32^{b}	
					20	NA	3.29^{c}	2.98^{c}	
					30 t ha^{-1}	NA	5.04^{d}	2.51^{d}	

Wheat straw	loamy sand	5.95	650	After 48 months	Average for biochar rates	NA	4.27^{a}	3.76^{a}	(Futa et al., 2020)
				After 60 months		NA	3.32^{a}	3.24^{b}	
				After 72 months		NA	3.10^{a}	2.47^{c}	
Cotton straw	Calcaric Fluvisol	16.2	450	Cotton	With NPK				(Liao et al., 2016)
					0	13.5^{b}	NA	NA	
					2.25	14.9^{a}	NA	NA	
					4.5 t ha^{-1}	15.4^{a}	NA	NA	
							NA	NA	
Wheat straw		20.1	350–550	Rice paddy	No fertilizer	54.40	0.91		(Chen et al., 2016)
					0	50.55	1.72	NA	
					20	43.09	2.01	NA	
					40 t ha^{-1}	LSD=4.56	LSD=0.74		
Sewage sludge	Sandy loam	8.87	600	No plant	0	2.64^{a}	0.11^{a}	NA	(Paz-Ferreiro et al., 2011)
				High organic matter	Sl 4	1.98^{ab}	0.12^{a}	NA	
					Sl 8%	0.58^{c}	0.10^{a}	NA	
					B4	1.71^{b}	0.16^{a}	NA	
					B 8%	1.22^{bc}	0.29^{b}	NA	

Sugarcane bagasse	Sandy loam 2years	1	350	Mash bean	No fertilizer				(Azeem et al., 2019)
					0	NA	4.37^b	17.83^b	
					5	NA	4.91^a	17.33^b	
					10 t ha^{-1}	NA	5.04^a	17.75^b	
					NPK fertilizer				
					0	NA	5.33^a	19.45^a	
					5	NA	5^a	17.62^b	
					10 t ha^{-1}	NA	5.20^a	17.70^a	
Sugarcane bagasse	Sandy loam 2 years	1	350	Wheat	No fertilizer				(Azeem et al., 2019)
					0	NA	4.45^a	17.95^a	
					5	NA	4.5^a	16.5^c	
					10 t ha^{-1}	NA	4.62^a	15.5^d	
		1			NPK Fertilizer				
					0	NA	5^a	17.20^b	
					5	NA	4.70^a	17.08^b	
					10 t ha^{-1}	NA	4.79^a	17.37^b	

Woody	Silt loam	13	500-600	Corn	NPK	58^{a}	NA	19^{b}	(Bera et al., 2016)
				3 years	DE	64^{a}	NA	19^{b}	
					NPK+ biochar 22 Mg ha $^{-1}$	44^{b}	NA	22^{a}	
					DE+biochar	62^{a}	NA	21^{a}	
Apple branch	Silt-clay	5	450	108 days	No urea				(Li et al., 2017)
					0	99.39^{c}	NA	0.194^{b}	
					1	85.19^{b}	NA	0.178^{a}	
					2	83.31^{ab}	NA	0.186^{ab}	
					4%	77.23^{a}	NA	0.179^{a}	
Apple branch	Silt-clay	5	450	108 days	Urea 0.2 g kg^{-1}				(Li et al., 2017)
					0	99.44^{c}	NA	0.218^{cd}	
					1	136.37^{e}	NA	0.221^{cd}	
					2	126.01^{d}	NA	0.224^{d}	
					4%	131.17^{de}	NA	0.209^{c}	

PL: *Poultry litter 5.00 t DM ha^{-1},* ***MF***: *100 kg N ha^{-1}, 40 kg P ha^{-1} and 120 kg K ha^{-1}, 336, 50, and 140 kg ha^{-1} N, P, and K (Bera et al., 2016),* ***DE:*** *Dairy manure effluent 168,000 l ha^{-1}. (Liao et al., 2016) NPK: s 300 kg N ha^{-1} urea, Triple super phosphate (105 kg P_2O_5 ha^{-1}) and potassium sulfate (60 kg K_2O ha^{-1}). (Futa et al., 2020) NPK: 70 kg ha^{-1} N (ammonium nitrate), 26 kg ha^{-1} P (triple superphosphate), and 66 kg ha^{-1} K (muriate of potash, KCl).*

3 Conclusions

Soil is the most important nutrient and water sources not only for crops, but for soil microflora. The biochar, an organic amendment, a carbon-enriched and porous substance, increases soil water and nutrient retention improving microbial activity. Carbonization of organic materials beyond sequestration of soil carbon, modifies its physical, chemical and biological features. Biochar induced pore structure and water movement changes in the soil improves the life conditions of microbes. It is important to mention that the influence of biochar on soil properties including microbes is highly variable because wide range of soil, biochar and plant variables such as (biochar type, pyrolysis temperature, experimental and environmental conditions, soil type, and agricultural management, etc.).

Although biochar has the ability to improve MBC, MBN, BSR in coarse textured soil except for sandy loam soils with low OC contents. The ability of well-OC content, coarse-textured soils to break down organic matter was diminished. Also, the ability of soil to convert urea into ammonium (the activity of the urea enzyme) has reduced in all soil and biochar types, with the exception of loamy sand soil treated with chicken litter biochar. Among other biochar types cotton and wheat straw biochar seemed to be a promising tool to enhance soil biological activity in coarse to medium textured soils under short term experiments. For example, cotton straw biochar positively affected MBN and BSR, even the lowest doses were enough for promoting β-glucosidase activity. Wheat straw biochar increased β-glucosidase and urease activity while just the lowest rate was positive for dehydrogenase improvement. Another good feedstock for MBC, the sugarcane bagasse has the same behavior as wheat straw regarding its enzyme activities. The critical function that biochar plays in modifying soil enzyme activity, which can also enhance nitrogen mineralization and utilization by activating N assimilation enzymes including glutamine synthetase, nitrate reductase, and glutamate synthase (Khan et al., 2022). Proper biochar application may provide better crop growing conditions, contributing to sustainable agriculture. One of the most important characters in biochar use is that the special technique used for its production makes it suitable for farm-scale conditions. Some of the investigators reported that biochar application may has a positive to neutral and even negative impact on crop growth. This is why its’ crucial to understand how the biochar is acting in different soils and crops when it is planned to apply locally.

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