Influence of soil properties and application rates on woody biochar potential for carbon mineralization and fertility sustainability of over-fertilization soils

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INTRODUCTION

In the tropics, however, naturally rapid mineralization of SOM is a limitation on the practical application of organic fertilizers, that is, in addition to repeated application at high dose and cost of application of organic materials, their rapid decomposition and mineralization may make a significant contribution to global warming . In addition, excessive manure application often causes heavy metal accumulation (Cu, Pb, Zn, etc.) in the soil, and the soluble fraction of these metals tends to increase due to desorption and remobilization of metals previously bound to the soil matrix, leading to enhanced crop uptake of heavy metals.

SOM has clearly declined in the arable lands of Taiwan since last several decades because of highly frequent tillage in association with high air temperature and rainfall, and farmers often apply excess compost to ensure adequate crop yield. However, in over-fertilization soils with manure compost little is known about the impact of different biochar application rates on the mineralization of manure compost in highly frequent tillage soil systems and how the interactions between biochar application rate and manure compost impact C sequestration and nutrient availability from soils.

OBJECTIVES

In vitro C mineralization kinetics of various addition rates of biochar in three soils were conducted in this study. We hypothesized that biochar may stabilize compost organic matter and diminish C mineralization. The aims of our research were

(1) To quantify the effects of woody biochar additions on C mineralization and soil fertility, and
(2) To evaluate the sustainability of woody biochar additions in terms of maintaining high-SOM contents and nutrient availability.

MATERIAL AND METHODS

Studied Soils

- ✓ The Pingchen (Pc) soil series: Slightly acid Oxisols (SAO), relict tertiary red soil in northern Taiwan.
- ✓ The Erhlin (Eh) soil series: Mildly alkaline Inceptisols (MAI), calcareous slate old alluvial parent material in central Taiwan.
- ✓ The Annei (An) soil series: Slightly acid Inceptisols (SAI), calcareous sandstone-shale new alluvial parent material in southern Taiwan.

Studied Biochar

- ➢ Biochar produced from lead tree (*Leucaena leucocephala* (Lam.) de. Wit) in an earth kiln was constructed by Forest Utilization Division, Taiwan Forestry Research Institute.
- ➢ The charring for earth kilns typically takes several days and reaches temperatures about 500 to 700°C.
- ➢ The biochars were homogenized and ground to < 2 mm mesh for the majority of analyses.

Table 1 Characteristics of biochar, compost, and studied soils.

Characteristics	Biochar	Compost	Pc soil	Eh soil	An soil
pH	9.9‡	8.41‡	6.1/5.0*	7.5/7.2*	6.5/6.2*
EC (dS m^{-1})	0.77‡/1.36§	3.79‡	0.45	2.21	0.81
Sand (%)			11	24	33
Silt (%)			30	36	33
Clay (%)			59	39	34
Soil Texture			Clay	Clay loam	Clay loam
Total C (%)	82.5	23.3	2.03	1.11	0.94
Total N (g kg^{-1})	6.99	22.6	2.71	2.32	1.58
Total P (g kg^{-1})	0.55	10.2	1.16	0.98	0.77
Ex. K (cmol(+) kg^{-1} soil)	1.91	6.43	0.32	0.29	0.21
Ex. Na (cmol(+) kg^{-1} soil)	1.26	1.09	0.31	0.26	0.37
Ex. Ca (cmol(+) kg^{-1} soil)	3.62	2.70	4.85	2.94	2.24
Ex. Mg (cmol(+) kg^{-1} soil)	0.40	2.72	0.64	0.80	0.36
CEC (cmol(+) kg^{-1} soil)	5.20	19.7	8.58	11.5	14.2
BS (%)	100	69	71	37	22
M3-P (mg kg^{-1})	96.6	6874	163	236	94.0
M3-K (mg kg^{-1})	616	8911	68.4	108	94.1
M3-Ca (g kg^{-1})	4.09	14.5	2.03	8.22	2.99
M3-Mg (mg kg^{-1})	278	3972	143	344	401
M3-Fe (mg kg^{-1})	65.5	396	524	589	1199
M3-Mn (mg kg^{-1})	20.9	188	29.0	213	185
M3-Cu (mg kg^{-1})	0.02	6.22	9.77	9.95	3.17
M3-Pb (mg kg^{-1})	ND**	1.23	10.8	11.7	1.54
M3-Zn (mg kg^{-1})	0.35	62.4	20.4	7.98	5.28

‡ The pH and electrical conductivity (EC) of biochar and compost were measured using 1:5 solid: solution ratio after shaking for 30 min in deionized water.
§ Biochar EC was measured after shaking biochar-water mixtures (1:5 solid: solution ratio) for 24 hr.
* Soil pH was determined in soil-to-deionized water ratio of 1:1 (g mL^{-1}) and in soil-to-1N KCl ratio of 1:1 (g mL^{-1})
** ND = not detected

Incubation Experiment

- Totally twelve treatments were performed in this study, and each treatment was set up in triplicate. All soil treatments added 5% commercially available swine manure compost as soil fertilizer, 2 times recommended amount of organic fertilizer in Taiwan.
- The application rate of biochar, including 0%, 0.5%, 1.0%, and 2.0% (w/w), equated to field applications of approximately 0, 12, 24, and 48 metric tons ha^{-1}, respectively, considering 2400 Mg of soil per hectare (soil bulk density equal to 1.2 Mg m^{-3} and an arable soil layer of 20 cm).
- The incubation experiment was run for 434 days with 23 times of. After sampling, the vessel with 10 ml of a 1M NaOH solution was removed, resealed, and stored until analysis for CO_2 and replace with fresh NaOH. A titrimetric determination method was used to quantify evolved CO_2 (Zibilske, 1984).
- Total mineralization coefficient (TMC) was calculated according to Díez et al. (1992) and Méndez et al. (2012) as follows:
  - TMC (mg CO_2-C g^{-1}C) = CO_2-C evolved / initial TOC Where CO_2-C evolved is expressed as mg CO_2-C 100 g^{-1} soil and initial total organic carbon (TOC) is expressed as g C 100 g^{-1} soil.
- Samples of the biochar-treated soil were collected after incubation days 434 for analysis of plant available nutrients using Mehlich-3 extraction (Mehlich, 1984). In order to compare the changes and quantify the impacts of soil-biochar amendments on nutrients, soil pH, TSC, TSN, TSP, exchangeable bases (K, Na, Ca, Mg), and CEC of the biochar-treated soil on day 434 were also measured.

RESULTS & DISCUSSION

■ BC addition significantly decreased (7-9%) the cumulative CO_2 emissions in SAO, non-significantly decreased (3-5%) in MAI, and significantly increased (8-15%) in SAI.

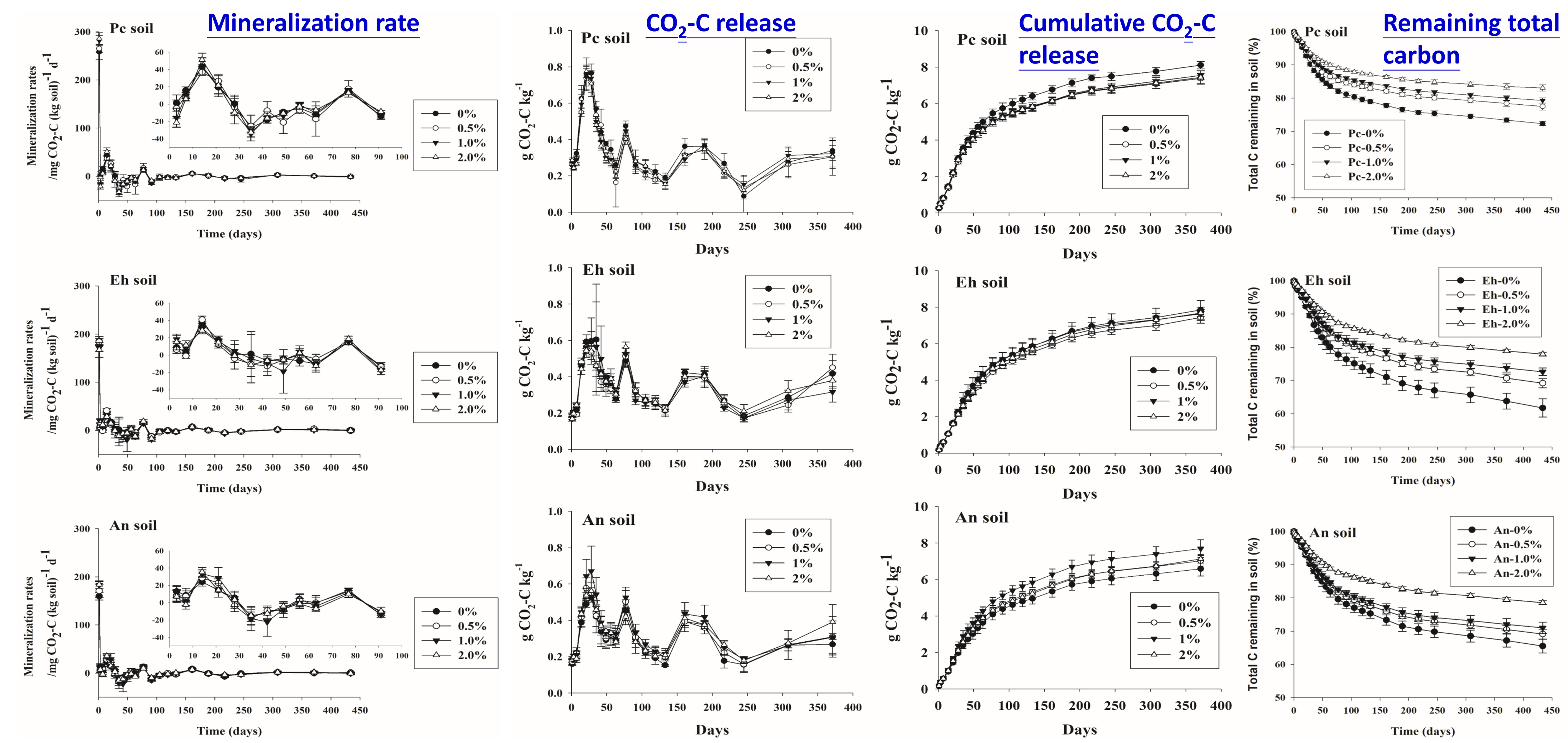
■ Respiration per unit of total organic carbon (TMC) of three studied soils significantly decreased with biochar addition increased.

■ The four treatments in SAO soil had significantly lower TMC value than MAI and SAI soil, indicated that the organic matter of SAO soil is conserved more efficiently and maintains the activity of the microorganisms responsible for soil organic matter biodegradation.

Table 2 CO_2-C evolved (mg C 100 g^{-1} dry weight) and total mineralization coefficient (TMC) for control and amended soils after incubation experiment.

Rate	CO_2 evolved (mg C 100 g^{-1} dry weight)	TMC (mg CO_2-C g^{-1} C)
Pc Soil (Oxisols)		
0%	842 ± 8.7 A	333 ± 3.4 A
0.5%	768 ± 18 B	278 ± 6.4 B
1.0%	783 ± 15 B	253 ± 4.7 C
2.0%	763 ± 21 B	207 ± 5.7 D
Eh Soil (Inceptisols)		
0%	829 ± 30 A	526 ± 19 A
0.5%	782 ± 18 A	423 ± 9.6 B
1.0%	797 ± 17 A	417 ± 8.7 B
2.0%	803 ± 10 A	355 ± 4.5 C
An Soil (Inceptisols)		
0%	692 ± 20 C	455 ± 14 A
0.5%	735 ± 18 BC	452 ± 11 A
1.0%	798 ± 24 A	464 ± 14 A
2.0%	747 ± 10 B	365 ± 4.9 B

† Means compared within a column followed by a different uppercase letter are significantly different at $p < 0.05$ using a one-way ANOVA (multiplecomparisons vs. studied soil + 0% biochar as a control).



■ After incubation, biochar has a mineralization potential in soils, even positive or negative, depending on different soil type.

■ The soil pH, exchangeable bases and CEC only showed minor increase with biochar addition increased.

■ The observed variations in Mehlich 3 extractable plant nutrient concentrations reflected the combined effects of fertilization (nutrients added with the biochar and manure compost), the leaching of nutrients, and the adsorption of nutrients by the soil and added biochar.

■ Adding biochar generally increased the levels of plant macronutrients and reduced the concentrations of micronutrients.

Table 3 Mean values of total soil carbon (TSC), nitrogen (TSN), and phosphorus (TSP), soil pH, exchangeable bases (K, Na, Ca, and Mg), and cation exchangeable capacity (CEC) of four treatments of three soils after 434-day incubations.

Rate	pH	Ex. K	Ex. Na	Ex. Ca	Ex. Mg	CEC	TSC	TSN	TSP	C/N
		--------------coml(+) kg^{-1} soil--------------					-----------g kg^{-1}-----------			
Pc Soil (Oxisols)										
0%	5.66 b	2.55 b	0.72 b	14.9 a	3.58 a	16.4 a	23.9 c	4.37 ab	1.55 c	5.5 c
0.5%	5.75 b	2.87 a	0.91 a	15.0 a	3.73 a	16.4 a	28.0 b	4.43 a	1.77 b	6.3 b
1.0%	5.76 b	2.40 b	0.73 b	14.4 a	3.36 a	16.0 a	31.8 a	4.28 b	1.69 bc	7.4 a
2.0%	5.93 a	2.55 b	0.63 b	15.5 a	3.41 a	16.3 a	34.5 a	4.27 b	2.21 a	8.1 a
Eh Soil (Inceptisols)										
0%	7.53 c	2.64 b	0.66 a	22.9 a	3.37 a	9.7 b	18.2 c	3.64 b	0.88 bc	5.0 c
0.5%	7.58 b	2.92 b	0.68 a	25.5 a	3.78 a	10.1 b	21.9 b	3.62 b	0.75 c	6.0 bc
1.0%	7.58 bc	2.92 ab	0.68 a	25.5 a	3.78 a	10.7 a	22.2 b	4.06 a	1.05 ab	5.5 b
2.0%	7.65 a	3.24 a	0.76 a	25.9 a	3.75 a	10.0 b	32.4 a	4.15 a	1.18 a	7.8 a
An Soil (Inceptisols)										
0%	7.04 c	2.14 c	0.59 a	13.9 a	4.24 a	13.4 a	13.7 c	2.86 b	1.26 a	4.8 c
0.5%	7.11 b	2.30 bc	0.54 a	15.3 a	4.52 a	13.3 a	18.3 b	2.89 b	1.11 a	6.3 b
1.0%	7.14 b	2.61 a	0.62 a	15.6 a	4.56 a	13.6 a	21.4 b	3.06 a	0.88 b	7.0 b
2.0%	7.24 a	2.45 ab	0.54 a	14.9 a	4.23 a	12.8 b	26.6 a	3.07 a	0.64 c	8.7 a

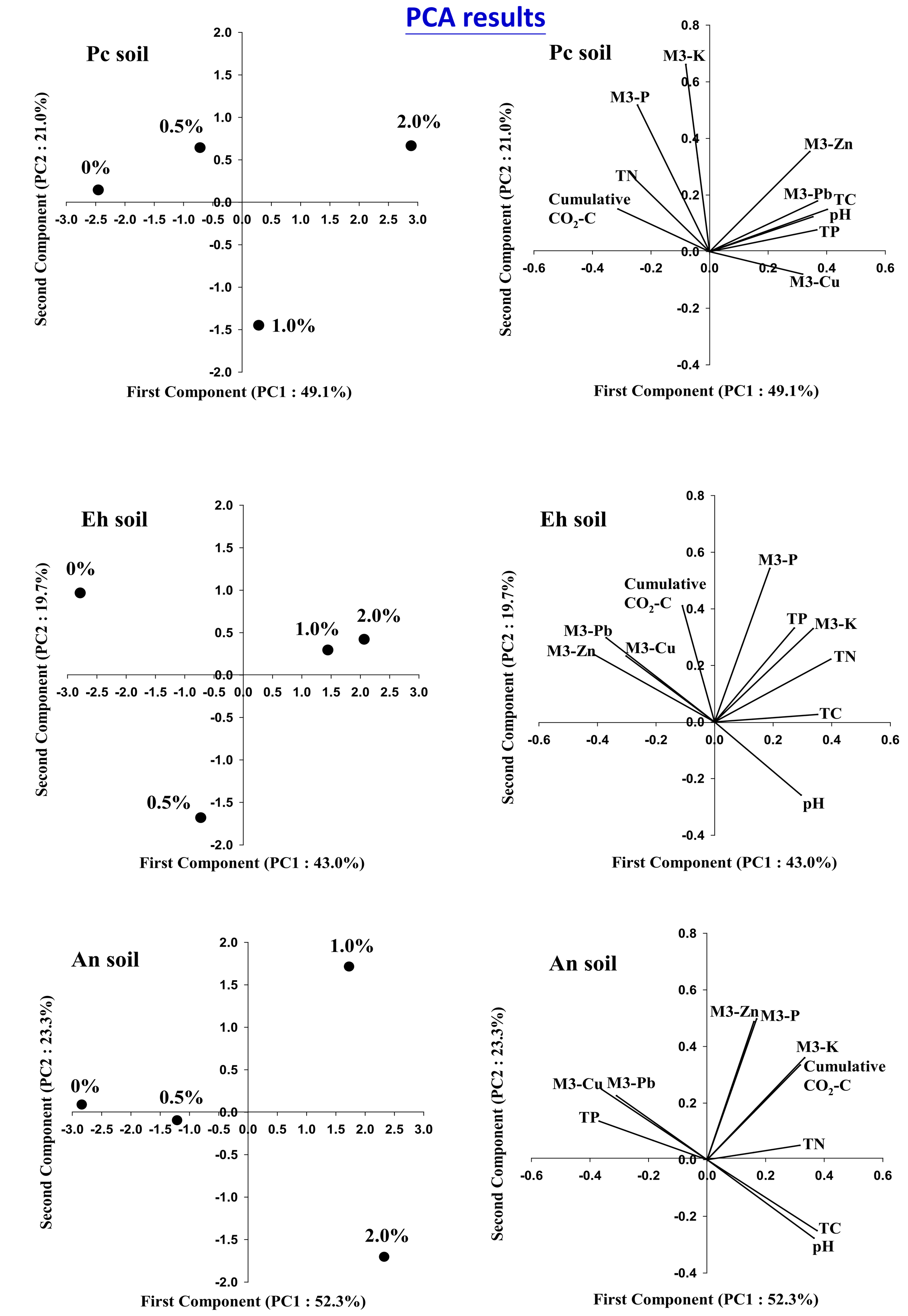
† Means compared within a column followed by a different lowercase letter are significantly different at $p < 0.05$ using a one-way ANOVA(multiple comparisons vs. studied soil + 0% biochar as a control).

Table 4 Mean values of soil fertility characteristics (Mehlich 3 extraction) (mg kg^{-1}) of four treatments of three soils after 434-day incubations.

Rate	P	K	Ca	Mg	Fe	Mn	Cu	Pb	Zn
Pc soil (Oxisols)									
0%	645 a	461 a	2701 b	533 a	953 a	5.7 ab	8.64 c	10.3 b	26.8 b
0.5%	653 a	467 a	3216 a	556 a	948 a	37.2 a	9.02 bc	10.2 b	28.6 b
1.0%	486 b	408 b	3118 a	444 b	739 b	31.6 c	9.36 ab	11.0 b	27.8 b
2.0%	537 b	457 a	3188 a	474 ab	777 b	3.5 bc	9.83 a	12.3 a	30.6 a
Eh soil (Inceptisols)									
0%	769 ab	474 c	7594 a	636 ab	694 ab	286 a	8.73 a	12.9 a	12.2 a
0.5%	671 b	481 bc	7799 a	611 b	621 b	271 a	7.79 b	11.4 b	10.6 b
1.0%	832 a	545 a	7142 a	712 a	739 a	310 a	7.60 b	10.7 b	10.3 b
2.0%	795 a	534 ab	7697 a	660 ab	707 ab	301 a	7.66 b	11.3 b	11.1 ab
An soil (Inceptisols)									
0%	476 b	384 c	3569 a	750 a	1257 a	197 a	1.70 a	0.84 a	9.48 c
0.5%	462 b	392 bc	3292 a	712 a	1147 a	186 a	1.66 a	0.67 ab	10.1 b
1.0%	564 a	474 a	3313 a	759 a	1200 a	196 a	1.54 b	0.57 bc	11.1 a
2.0%	470 b	437 ab	3648 a	726 a	1183 a	194 a	1.29 c	0.48 c	9.53 bc

† Means compared within a column followed by a different lowercase letter are significantly different at $p < 0.05$ using a one-way ANOVA(multiple comparisons vs. studied soil + 0% biochar as a control).

PCA results



■ Three studied soils over-fertilization with manure compost were less sensitive to the addition of BC which could be attributed to higher buffer capacity and finer texture (silt + clay > 60%).

■ In addition, adding 2.0%BC in SAO soil and 1.0%BC in MSI and SAI soils led to substantial improvement in some soil fertility, for example, total carbon, total nitrogen, total phosphorus, soil pH, available K and P.

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References

Díez, J.A., Polo, A., Guerrero, F., 1992. Effect of seweage sludge on nitrogen availability in peat. Biol. Fertil. Soils 13, 248-251.
Mehlich, A. 1984. Mehlich-3 soil test extractant: a modification of Mehlich-2 extractant. Commoun. Soi. Sci. Plant Anal. 15:1409-1416.
Méndez, A., Gómez, A., Paz-Ferreiro, J., Gascó, G., 2012. Effects of sewage sludge biochar on plant metal availability after application to a Mediterranean soil. Chemosphere 89, 1354-1359.
Zibilske, L. M. 1994. Carbon Mineralization, In: Weaver, R. W., Angle, J. S., Bottomly, P. (eds.): Methods of Soil Analysis, Part 2, Microbiological and Biochemical Properties. Soil Science of America Inc., Madison, Wisconsin, USA, pp. 835–863.