https://doi.org/10.61308/CMII1237

Influence of biochar on the microflora in reclaimed soils in the area of the Medet mine from the Asarel-Medet metallurgical plant in Bulgaria

Jonita Perfanova*, Irena Atanassova, Milena Harizanova, Lyuba Nenova, Maya Benkova, Tsetska Simeonova, Mariela Stoykova

ISSAPP „N. Poushkarov“, 1080, Sofia, Agricultural Academy - Sofia, Bulgaria

*E-mail: *JPerfanova@gmail.com*

Citation: Perfanova, J., Atanassova, I., Harizanova, M., Nenova, L., Benkova, M., Simeonova, Ts., & Stoykova, M. (2025). Influence of biochar on the microflora in reclaimed soils in the area of the Medet mine from the Asarel-Medet metallurgical plant in Bulgaria. *Bulgarian Journal of Crop Science,* 62(4) 91-97.

Abstract: The influence of biochar on the microflora in reclaimed soils from the area of the Medet mine, part of Asarel-Medet metallurgical plant, under the conditions of a 6 month incubation experiment, was evaluated. Four levels of biochar addition were studied 1%, 5%, 10% and 20%. Biochar positively affected the ammonifying microorganisms and mineral nitrogen-utilizing bacteria. On at the sixth month there was a significant increase in the amount of microorganisms associated with the processes of mineralization and ammonification. Actinomycetes have a greater distribution on the 3rd month along a 6 month period, but they exceeded the amounts of the control variants. Biochar favors the development of microscopic fungi and during both stages of the study they show a significant increase. The high percentage of biochar in the variants T4 and T7 suppresses the abondance of cellulose-decomposing microorganisms.

Key words: main groups of soil microorganisms; biochar; reclaimed soils

INTRODUCTION

Microorganisms play an indispensable role in soil, helping the natural processes to be maintained. Microbiological processes are influenced by a number of factors, one of which is the content of chemical elements in soil. Increased levels of heavy metals, as a result of mining activities, reduce the microbial population and biodiversity. However, some soil microorganisms show tolerance and utilize heavy metals in their systems, and as such they are used for bioremediation of contaminated soils. Microscopic fungi and actinomycetes were found to be most resistant to heavy metals. This shows that it is possible to use microbiological methods to assess the degree of soil contamination with different metals and compounds (Maliszewska et al., 1985; Abdu et al., 2017; Chu, 2017; Inobeme, 2021).

Biochar stimulates the activity of various agriculturally important soil microorganisms and can significantly influence the microbiological properties of soils. The presence and distribution of pore sizes in biochar provide a suitable habitat for many microorganisms by protecting them from predation and desiccation and by providing many of their diverse carbon, energy and mineral nutrient needs. With the interest in using biochar to promote soil fertility, much scientific research is being conducted to better understanding how it affects the physical and chemical properties of soils and their suitability as a habitat for microbiota. Because soil organisms provide myriad of ecosystem services, understanding how biochar addition to soil can affect soil ecology is critical to ensuring that soil quality and soil subsystem integrity are maintained (Thies & Rillig, 2009)

Cu contamination can negatively affect the presence of soil microorganisms (Wilke et al., 2005, Vázquez-Blanco et al., 2020), but in our

previous study (Atanassova et al., 2023) no clear relationships between Cu content and microflora were established in five out of eight analysed sites ranging from Cu 128-423 mg/kg, that exceeded the maximum permissible loads for Cu contents, as regulated by the National legislation.

The aim of the present research is to determine the influence of biochar on the microflora in soils of disturbed terrains from mining activity with subsequent reclamation in Asarel-Medet area.

MATERIAL AND METHODS

Based on the initial research, three out of a total of eight sites were selected and an incubation experiment was carried out. The selected soils were from T1, T4 – "Large southern embankment" and T7 from the Tailings of the "Medet mine", to which biochar was added at different percentages. Detailed information on soils genesis and properties is provided in Atanassova et al. (2023). For a period of six months, the dynamics of a number of chemical elements was tracked and analyzed. Water extracts were used to determine the concentration of Ca, Mg and Cr, as described by Katoh et al. (2012) and results are presented in Table 1. These elements were of major importance for the dynamics of the microorganisms analyzed in this study. Four levels of biochar (BC) addition were studied 1%, 5%, 10% and 20%.

The incubation experiments were carried out in a climatic chamber with a phytotron system (KK 350 *FIT DS–POL-EKO*, 2022) (Stoykova et al., 2024).

Soils have acid pH (T1 pH 4.6; T4 pH 4.9; T7 pH 4.7) and low organic C content (T1 OC 1%; T4 OC 1.4%; T7 0.9).

Biochar was found to enhance microbial activity and improve soil properties in a long-term cultivated Fluvisol deficient of organic carbon (Petkova et al., 2018; Atanassova et al., 2022a, b; Benkova et al., 2022). This type of BC produced at comparatively low temperature is more suitable for removing polar organic and inorganic pollutants (Qiu et al. 2022), because it contains higher fraction of polar functional groups,

Table 1. Soluble concentrations of the metal cations Ca, Mg and Cr at various additions of biochar after three and six months of incubation.

Variants	Ca, ppb		Mg, ppb		Cr, ppb	
	Month III	Month VI	Month III	Month VI	Month III	Month VI
T1 Control	917,71	1751,82	89,79	203,28	0,57	2,02
T1 1% BC	1841,29	2292,50	250,72	258,59	1,21	2,17
T1 5% BC	740,13	699,08	98,28	92,91	2,87	1,68
T1 10% BC	167,19	327,51	7,47	49,54	1,38	3,94
T1 20% BC	2609,85	507,01	324,76	70,91	3,48	2,17
T4 Control	574,73	899,29	208,59	344,51	3,70	5,34
T4 1% BC	657,59	763,60	233,65	276,02	0,90	1,98
T4 5% BC	468,29	245,10	172,22	90,70	1,90	1,63
T4 10% BC	123,78	100,72	6,15	34,42	1,63	1,81
T4 20% BC	163,10	42,78	6,54	20,75	1,85	1,91
T7 Control	1674,20	3478,60	582,39	959,32	1,64	1,16
T7 1% BC	1679,78	3237,82	571,87	876,03	0,68	1,73
T7 5% BC	1856,85	1509.00	590,61	408,58	4,50	1,78
T7 10% BC	2623,88	2825,08	819,55	731,65	3,85	4,41
T7 20% BC	5567,14	3243,77	1538,66	767,94	1,61	4,25

through which metal cations (including OH species and other complexes) are held by specific and non-specific (electrostatic) adsorption processes (Li et al., 2022).

To analyze the microflora, two samples were taken on the third and sixth month of the incubation experiment. The amount of the main groups of soil microorganisms was determined by the method of ten-fold dilutions by sowing soil suspensions on selective agar nutrient media (Grudeva et al., 2006). The following physiological and taxonomic groups of soil microorganisms were determined: ammonifying microorganisms, on meat-peptone agar (MPA), microscopic fungi - on acidified Chapek's medium, actinomycetes and mineral nitrogen-utilizing bacteria - starch-ammonia agar (SAA) and cellulose-decomposing microorganisms on Hutchinson's medium. Data were statistically processed by ANOVA (LSD test at $p < 0.05$).

RESULTS AND DISCUSSION

On the third month of incubation following biochar addition into the soil, a decrease in ammonifying microorganisms was reported, compared to the control variants (Table 2). On the sixth month, the ammonifying microorganisms were generally significantly increased, both in relation to their distribution on the third month and in relation to the controls. This shows that biochar positively affects this group of soil microorganisms, but a period of time is required for their adaptation and activation. From the obtained results, it can be seen that, of all the studied variants, the ammonifying microorganisms decreased on the sixth month compared to the third month only for the variants T4 10% BC (10.2 10^6 CFU g^{-1} soil and T4 20% BC (14.0 10^6 CFU g^{-1} soil). On the third month, 13.4 – 20.8 10^6 CFU g^{-1} soil were reported, respectively. This may be due

Table 2. Main groups of soil microorganisms – month III of biochar application

Variants	Ammonifying microorganisms	Mineral nitrogen-utilizing bacteria	Actinomycetes	Microscopic fungi	Cellulose-decomposing microorganisms
	10^6 CFU/g soil			10^3 CFU/g soil	
T1 Control	**20,1** ^{c}	**19,0** ^{c}	**0,8** ^{a}	**10** ^{a}	**7** ^{a}
T1 1% BC	**7,6** ^{a}	**9,0** ^{ab}	**6,6** ^{b}	**36** ^{b}	**26** ^{b}
T1 5% BC	**19,8** ^{b}	**12,0** ^{b}	**1,6** ^{a}	**30** ^{b}	**40** ^{c}
T1 10% BC	**7,6** ^{a}	**4,6** ^{a}	**2,4** ^{a}	**42** ^{c}	**42** ^{c}
T1 20% BC	**10,0** ^{a}	**5,0** ^{a}	**2,2** ^{a}	**78** ^{d}	**43** ^{c}
LSD P≤0,05	44,35	22,62	7,39	4,65	9,70
T4 Control	**19,2** ^{c}	**23,4** ^{cb}	**0,4** ^{a}	**28** ^{a}	**30** ^{b}
T4 1% BC	**4,2** ^{a}	**18,8** ^{ab}	**3,0** ^{c}	**54** ^{b}	**60** ^{d}
T4 5% BC	**11,6** ^{b}	**12,8** ^{a}	**3,0** ^{bc}	**68** ^{c}	**38** ^{bc}
T4 10% BC	**13,4** ^{b}	**21,2** ^{bc}	**2,8** ^{bc}	**56** ^{b}	**49** ^{c}
T4 20% BC	**20,8** ^{c}	**22,0** ^{ab}	**1,6** ^{ab}	**46** ^{b}	**18** ^{a}
LSD P≤0,05	16,87	38,09	6,16	6,69	8,92
T7 Control	**22,2** ^{a}	**12,4** ^{ab}	**2,0** ^{a}	**20** ^{b}	**39** ^{b}
T7 1% BC	**14,6** ^{b}	**21,0** ^{ab}	**3,2** ^{a}	**28** ^{bc}	**46** ^{b}
T7 5% BC	**14,4** ^{b}	**21,4** ^{b}	**2,2** ^{a}	**12** ^{a}	**47** ^{b}
T7 10% BC	**11,6** ^{b}	**12,6** ^{a}	**2,2** ^{a}	**46** ^{d}	**29** ^{a}
T7 20% BC	**19,2** ^{b}	**17,0** ^{ab}	**4,6** ^{a}	**32** ^{c}	**29** ^{a}
LSD P≤0,05	50,70	43,88	15,65	3,63	10,75

to the low content of calcium and magnesium, at T4 10% BC (Ca - 100.72 ppb, Mg - 34.42 ppb) and T4 20% BC (Ca - 42.78 ppb, Mg - 20.75 ppb), on the sixth month. In the remaining three variants of T4, the amount of these chemical elements is Ca 245.1 ÷ 899.29 ppb and Mg 90.7 ÷ 344.51 ppb. It can be determined that calcium and magnesium have a favorable effect on the course of ammonifying bacteria.

Mineral nitrogen-utilizing bacteria, in the variants of T1 and T4, decrease after the application of biochar to the soil. On the sixth month, a recovery of their development was reported, except for the variant T4 20% BC (Table 3). In this variant, mineral nitrogen-utilizing bacteria were lower in number (17.0 10^6 CFU g^{-1} soil) compared to the control (22.2 10^6 CFU g^{-1} soil) and their quantity on the third month (22.0 10^6 CFU g^{-1} soil). It is possible that the high amount of biochar inhibits the development of these microorganisms in the T4 soil conditions. In the T7 variants, the positive influence of biochar can be observed already on the third month. Mineral nitrogen-utilizing bacteria have a greater presence compared to the control (12.4 10^6 CFU g^{-1} soil), which is more pronounced in variants T7 1% BC (21.0 10^6 CFU g^{-1} soil) and T7 5% BC (21.4 10^6 CFU g^{-1} soil). In the variants T7 10% BC (12.6 10^6 CFU g^{-1} soil) and T7 20% BC (17.0 10^6 CFU g^{-1} soil) mineral nitrogen-utilizing bacteria have a lower distribution, but on the sixth month their number significantly increases, 37.1 10^6 CFU g^{-1} soil and 49.6 10^6 CFU g^{-1} soil, respectively.

The positive influence of biochar on the distribution of actinomycetes was established. On the third month of the experiment, an increase in actinomycetes was recorded, in all variants, compared to the controls. On the sixth month in some of the variants, the actinomycetes decreased compared to the third month, but remained in greater

Table 3. Main groups of soil microorganisms – month VI, of biochar application

Variants	Ammonifying microorganisms	Mineral nitrogen-utilizing bacteria	Actinomycetes	Microscopic fungi	Cellulose-decomposing microorganisms
	10^6 CFU/g soil			10^3 CFU/g soil	
T1 Control	**19,6** ^{b}	**17,1** ^{a}	**0,6** ^{a}	**40** ^{a}	**46** ^{ab}
T1 1% BC	**8,0** ^{a}	**23,4** ^{bc}	**0,6** ^{a}	**44** ^{a}	**56** ^{bc}
T1 5% BC	**58,0** ^{d}	**24,4** ^{cd}	**0,8** ^{b}	**72** ^{c}	**64** ^{c}
T1 10% BC	**9,0** ^{a}	**19,6** ^{ab}	**1,4** ^{c}	**64** ^{b}	**64** ^{c}
T1 20% BC	**33,0** ^{c}	**30,0** ^{d}	**0,6** ^{a}	**62** ^{b}	**42** ^{a}
LSD P≤0,05	21,22	62,08	0,46	3,81	15,09
T4 Control	**32,2** ^{d}	**22,2** ^{b}	**1,6** ^{a}	**68** ^{ab}	**71** ^{b}
T4 1% BC	**25,0** ^{c}	**35,6** ^{cd}	**3,8** ^{c}	**70** ^{ab}	**89** ^{b}
T4 5% BC	**34,8** ^{e}	**35,9** ^{d}	**2,0** ^{ab}	**66** ^{a}	**66** ^{a}
T4 10% BC	**10,2** ^{b}	**30,1** ^{bc}	**3,2** ^{bc}	**78** ^{b}	**73** ^{b}
T4 20% BC	**14,0** ^{a}	**17,0** ^{a}	**1,8** ^{ab}	**90** ^{c}	**68** ^{a}
LSD P≤0,05	8,19	64,30	7,62	5,79	13,49
T7 Control	**23,8** ^{a}	**16,2** ^{a}	**2,4** ^{a}	**40** ^{a}	**31** ^{b}
T7 1% BC	**55,0** ^{c}	**18,7** ^{a}	**3,2** ^{a}	**58** ^{b}	**18** ^{a}
T7 5% BC	**57,0** ^{c}	**38,9** ^{bc}	**2,4** ^{a}	**66** ^{bc}	**43** ^{c}
T7 10% BC	**37,8** ^{b}	**37,1** ^{ab}	**5,2** ^{a}	**72** ^{bc}	**36** ^{b}
T7 20% BC	**56,0** ^{c}	**49,6** ^{c}	**3,6** ^{a}	**74** ^{c}	**16** ^{a}
LSD P≤0,05	34,40	46,90	14,92	8,23	5,45

quantities than the control variants. According to Xu et al. (2020), the mechanism of the effect of biochar on soil microbial populations remains unclear. The authors reported that the prevalence of actinomycetes decreased with biochar application to the soil. A number of other studies (Perfanova et al., 2020, Abdulrahman et al., 2016; Yunyan et al., 2017; Sun et al., 2013, etc.) found that biochar significantly increased soil actinomycete populations.

The results obtained for the distribution of the microscopic fungi showed a large increase during both stages of the study. Microscopic fungi increased, both relative to the control variants, and on the sixth month compared to the third, except for variants - T7 5% BC (month III), T1 20% BC and T4 5% BC (month VI). The decrease in the number of microscopic fungi in the T1 20% BC variant, on the sixth month, compared to the third month, we attribute to the chromium content of the soil. On the third month, the content of chromium was reported to be 3.48 ppb and 78 10^3 CFU g^{-1} soil microscopic fungi, while on the sixth month their amount was Cr 2.17 ppb and 62 10^3 CFU g^{-1} soil, respectively. The trend is similar in the control variants, on the third month Cr is 0.57 ppb / microscopic fungi - 10 10^3 CFU g^{-1} soil and on the sixth month Cr is 2.02 ppb / microscopic fungi - 40 10^3 CFU g^{-1} soil. In the initial stages of individual sites from Asarel-Medet area, it was also found that microscopic fungi have a good development at higher amounts of chromium in soil (Perfanova et al., 2024).

Biochar provides a favorable habitat and food source for microscopic fungi, which creates microorganism-biochar-soil associations that improve soil properties (Prakongkep et al., 2021).

After the addition of biochar, on the third month in the variants of T1, the cellulose decomposing microorganisms enhance relative to the increase in the percentage of biochar. On the sixth month, the trend is maintained, except for the variant T1 20% BC, where the number of cellulose-decomposing microorganisms slightly decreases compared to the control. During both periods of the study, a lower prevalence of cellulose-decomposing microorganisms was observed in the variants T4 20% BC and T7 20% BC. A longer period of time is probably required for this group of microorganisms to adapt to the high percentage of biochar under the T4 and T7 soil conditions.

CONCLUSIONS

After the introduction of biochar into the reclaimed soils, microbiological processes take place with different intensity, depending on the percentage content of BC and the period of study. Biochar has a positive effect on ammonifying microorganisms and mineral nitrogen-utilizing bacteria, but a period of time is required for their adaptation and activation. On the sixth month after the introduction of biochar into the soil, the ammonification and mineralization processes are actively taking place. Actinomycetes have a greater distribution on the third month along a 6 month period, compared to the sixth, but they remain in larger quantities compared to the control variants. Biochar favors the development of microscopic fungi and during both stages of the study they show a large increase. The high percentage of biochar in variants T4 and T7 suppresses the activity of cellulose-decomposing microorganisms.

Acknowledgements

The study was funded by the National Science Fund, Ministry of Education and Science, Project No КП-06-Н66/2.

REFERENCES

Abdu, N., Abdullahi, A. & Abdulkadir, A. (2017). Heavy metals and soil microbes. *Environmental Chemistry Letters, volume 15, pages 65–84.*

Abdulrahman, D., Othman, R. & Saud, H. (2016). Effects of empty fruit bunch biochar and nitrogen-fixing bacteria on soil properties and growth of sweet corn. *Malaysian Journal of Soil Science, Vol. 20, 177-194.*

Atanassova, I., Benkova, M., Nenova, L., Harizanova, M., Ilinkin, V., Kirilov, I., Dimitrov, E. & Simeonova, Ts. (2023). Geogenic and pedogenic sources

of metals in reclaimed technosols from the area of Asarel - Medet non-ferrous smelter in Bulgaria. *Journal of Environmental Protection and Ecology 24, No 6, 1857–1866.*

Atanassova, I., Harizanova, M., Benkova, M., Simeonova, Ts. & Nenova, L. (2022a). Organic molecular markers in soils ameliorated with biochar. *C R Acad Bulg Sci 75:467–474. https:// doi. org/ 10. 7546/ CRABS. 2022. 03. 18.*

Atanassova, I., Harizanova, M., Benkova, M. & Doerr, S. H. (2022b). Changes in organic molecular marker signatures in soils amended with biochar during a three-year experiment with maize on a Fluvisol. *J Hydrol Hydromech 70:1–9.*

https:// doi. org/ 10. 2478/ johh- 2022- 0025.

Atanassova, I., Nenova, L., Simeonova, Ts., Benkova, M., & Ilinkin, V. (2024). Effect of biochar on heavy metal solubility and speciation in Technogenic soils around Aurubis copper smelter in Bulgaria. *Biologia*. https://doi.org/10.1007/s11756-023-01590-5

Benkova, M., Nenova, L., Simeonova, Ts., Petrova, V., Mikova, A. & Atanassova, I. (2022). Impact of oak wood biochar and nitrogen fertilizer on soil properties and maize biomass growth. *Forestry Ideas 28*, pp.241–253.

Chu, D. (2017). Effects of heavy metals on soil microbial community. IOP Conference Series: Earth and Environmental Science, *3rd International Conference on Advances in Energy Resources and Environment Engineering, Harbin, China, Volume 113*, DOI 10.1088/1755-1315/113/1/012009.

Grudeva, V., Naumova, S., Gocheva, B., Nedeva, T. & Antonova-Nikolova, S. (2006). Manual Microbiology. University Publishing House „St. Kl. Ohridski „, Sofia.

Inobeme, A. (2021). Effect of Heavy Metals on Activities of Soil Microorganism. In: Adetunji, C.O., Panpatte, D.G., Jhala, Y.K. (eds) Microbial Rejuvenation of Polluted Environment. *Microorganisms for Sustainability*, vol 27, pp 115–142. Springer, Singapore. https://doi.org/10.1007/978-981-15-7459-7_6

Katoh, M., Masaki, S., & Sato, T. (2012). Single-step extraction to determine soluble lead levels in soil. *Int J GEOMATE* 3, p. 375.

Li, Q., Wang, Y., Li, Y., Li, L., Tang, M., Hu, W … & Ai, S. (2022). Speciation of heavy metals in soils and their immobilization at micro-scale interfaces among diverse soil components. *Sci Total Environ* 825:153862.

https:// doi. org/ 10. 1016/j. scito tenv. 2022. 153862

Maliszewska, W., Dec, S., Wierzbicka, H. & Woźniakowska, A. (1985). The influence of various heavy metal compounds on the development and activity of soil micro-organisms. *Environmental Pollution Series A, Ecological and Biological*, Volume 37, Issue 3, Pages 195-215.

Perfanova, J., Petkova, G. & Atanassova, I. (2020). Influence of organic soil improvers on the microflora of Leached Smolnitsa and Alluvial-meadow soil. Proceedings of the scientific forum with international participation „Ecology and agrotechnologies – fundamental science and practical realization“, volume 1, 166 – 173 (Bg).

Perfanova, J., Atanassova, I., Harizanova, M. & Kirilov, I. (2024). Microbiological properties of disturbed terrains from mining activity with subsequent reclamation in the area of Asarel-Medet. *Journal of Mountain Agriculture on the Balkans*, 27, in press.

Petkova, G., Nedyalkova, K., Mikova, A. & Atanassova, I. (2018). Microbiological characteristics of biochar amended alluvial meadow soil. *Bulgarian Journal of Agricultural Science*, 24 (Suppl. 2), 81-84.

https://journal.agrojournal.org/page/en/archive.php?issue=87 (SJR 0.223)

Prakongkep, N., Gilkes, R., Wisawapipat, W., Leksungnoen, P., Kerdchana, C., Inboonchuay, T., Delbos, E., Strachan, L., Ariyasakul, P., Ketdan, C. & Hammecker, C. (2021). Effects of Biochar on Properties of Tropical Sandy Soils Under Organic Agriculture. Journal of Agricultural Science; Vol. 13, No. 1. Published by Canadian Center of Science and Education p. 1-17.

Qiu, M., Liu, L., Ling, Q., Cai, Y., Yu, S., Wang, S.… &Wang, X. (2022). Biochar for the removal of contaminants from soil and water: a review. Biochar 4, 19 p.

Stoykova, M., Atanassova, I., Benkova, M., Simeonova, Ts., Nenova, L., Harizanova, M. & Atsenova, M. (2024). Positive Effect of Biochar Application on Soil Properties: Solubility and Speciation of Heavy Metals in Non-Acidic Contaminated Soils near a Steel Metallurgical Plant in Southeastern Europe. *Sustainability*. 16(16), 6891. https://doi.org/10.3390/su16166891

Sun, D., Meng, J. & Chen, W. (2013). Effects of abiotic components induced by biochar on microbial communities. Acta Agriculturae Scandinavica, Section B — Soil & Plant Science. Volume 63, Issue 7, Pages 633-641.

Thies, B. & Rillig, M. (2009). Characteristics of Biochar: Biological Properties. Biochar for Environmental Management, Book, Pages 22.

Vázquez-Blanco, R., Arias-Estévez, M., Bååth, E. & Fernández-Calviño, D. (2020). Comparison of Cu salts and commercial Cu based fungicides on toxicity towards microorganisms in soil. *Environmental Pollution*, Volume 257, 113585.

Wilke, B., Mai, M., Gattinger, A., Schloter, M. & Gong, P. (2005). Effects of fresh and aged copper contaminations on soil microorganisms. *Journal of plant nutrition and soil science*, Volume 168, Issue 5, Pages 668-675.

Yunyan, M., Wanli, X., Guangmu, T., Meiying, G. & Quanhong, X. (2017). Effect of cotton stalk biochar application on soil microflora of continuous cotton cropping under use of antagonistic actinomycetes[J]. *Chinese Journal of Eco-Agriculture*, 25(3): 400-409. DOI: 10.13930/j.cnki.cjea.160583

Xu, W., Whitman, W., Gundale, M., Chien, C. & Chiu, C. (2020). Functional response of the soil microbial community to biochar applications. Global change biology bioenergy. https://doi.org/10.1111/gcbb.12773

Received: March, 08, 2025; *Approved:* May, 25, 2025; *Published:* August, 2025