

Biochar blended with sheep manure and biogas station residue in different ratios can significantly influence soil properties

Vladimír Šimanský^{1*}, Elżbieta Wójcik-Gront², Ján Horák³, Žaneta Pauková⁴, Natalya Buchkina⁵

¹ Institute of Agrochemistry and Soil Science, Faculty of Agrobiology and Food Resources, Slovak University of Agriculture, 949 76 Nitra, Slovakia.

² Department of Biometry, Institute of Agriculture, Warsaw University of Life Sciences-SGGW, Nowoursynowska 159, 02–776 Warsaw, Poland.

³ Institute of Landscape Engineering, Faculty of Horticulture and Landscape Engineering, Slovak University of Agriculture, 949 76 Nitra, Slovakia.

⁴ Institute of Law and Sustainable Development, Faculty of European Studies and Regional Development, Slovak University of Agriculture, Tr. A. Hlinku 2, 949 76 Nitra, Slovakia.

⁵ Department of Soil Physics, Physical Chemistry and Biophysics, Agrophysical Research Institute, 195220, St. Petersburg, Russia.

* Corresponding author. E-mail: vladimir.simansky@uniag.sk

Abstract: Biochar, produced via biomass pyrolysis, is increasingly recognized for its potential in soil health enhancement. This study investigates the impact of compost, biochar blended with sheep manure in 50:50 ratio (BS1), biochar blended with sheep manure and biogas station residue in 33:33:33 (BS2), and 30:50:20 (BS3) ratios on chemical characteristics and organic substances in the leachates, focusing on the interplay between these components. The experimental design included leaching tests with the abovementioned treatments in a controlled environment. Results indicate significant differences in pH, electrical conductivity, and the content of organic substances between the treatments, suggesting that biochar substrates can positively influence physico-chemical characteristics and nutrient dynamics after their incorporation into the soils. Notably, the BS1 demonstrated enhanced water-soluble salts, cold-water-soluble carbon, and humic substances release potential compared to the other studied treatments. Principal component analysis further elucidated the complex relationships between the measured parameters, indicating the importance of biochar-based substrates careful mixing for sustainable agricultural practices to improve soil fertility and carbon sequestration.

Keywords: Biochar substrates; Carbon; Compost; Digestate; Humic substances; Sheep manure; Soil amendments.

INTRODUCTION

Biochar, a carbon-rich material produced through biomass pyrolysis, has gained significant attention in recent years due to its potential to sequester carbon and improve soil health (Horák et al., 2020; Rončák et al., 2023; Shackley et al., 2016; Shen, 2024; Šimanský et al., 2018). As global interest in sustainable agricultural practices intensifies, biochar is increasingly recognized as a valuable agronomic ameliorant capable of enhancing such soil properties as nutrient retention, microbial activity, and overall soil environment (Githinji et al., 2020; Horák and Šimanský, 2017; Lehmann and Joseph, 2015; Šimanský et al., 2022). Biochar production utilizes waste materials, thereby contributing to the circular economy and addressing challenges associated with waste disposal (Matsumoto, 2021). However, while biochar holds promise as a soil amendment, various studies indicate that its effectiveness can be highly variable (Cao et al., 2017).

One of the major challenges concerning biochar application in agriculture is the unclear mechanisms through which different types of biochar influence properties of various soil types. Factors such as feedstock source, pyrolysis conditions, and the interaction between biochar and other soil amendments can significantly affect biochar's properties and performance (Are, 2019; Schmidt and Wilk, 2019). Furthermore, nutrient imbalances associated with specific biochar applications, such as a lack of essential macronutrients and micronutrients, can hinder crop growth and soil health (Sohi et al., 2010). Given these

limitations, producers and researchers are exploring ways to enhance the properties of biochar and develop biochar-based substrates. These innovations aim to minimize the negative aspects of conventional biochar while maximizing its agronomic benefits. As the agricultural sector increasingly seeks sustainable practices, biochar has emerged as a promising solution for improving soil health and fertility. However, for farmers to fully use the benefits of biochar without the need for additional fertilization – whether organic or mineral – the production of biochar-based substrates is becoming a focal point. Such substrates are designed to have a balanced nutrient profile, significantly reducing the labor operations associated with traditional soil amendments. By enhancing soil properties, biochar substrates offer a comprehensive product that can be effectively utilized across various soil types and climatic conditions. Manufacturers are committed to optimizing biochars to meet the diverse needs of agricultural practices, ensuring that farmers can achieve healthier crops with minimal supplementary inputs (Lehmann and Joseph, 2015).

A potential advantage of biochar substrates compared to pure biochar could be their lower cost. For example, Šimanský et al. (2020) published an economic evaluation of pure biochar application in various doses. At that time, given the current market prices of the biochar production, the results indicated a high unprofitability of pure biochar application to the soil for farmers. The farmers' inputs when applying this model were disproportionately high relative to the yield increase. Similar data were presented in IBI (2015). Biochar is a component of biochar

substrates, and thus their overall unit production cost can be significantly lower, while the final product (biochar substrate) eliminates the negatives of pure biochar.

Organic amendments application to soils generally brings several positive benefits for farmers. For example, incorporated compost improves soil structure, increases water retention, enhances microbial activity, and improves nutrient soil composition. Composts help to increase soil organic carbon levels (Šimanský et al., 2021), enhance soil fertility, and reduce soil erosion (Sharma et al., 2024). The results of García et al. (2018) demonstrate significant increases in crop yields with compost application due to its nutrient content and improvement in soil health. Through farmyard manure application, such primary nutrients for plant growth as nitrogen, phosphorus, and potassium are added to soils, while soil structure and biological activity are also being improved. However, farmyard manure application can lead to a short-term increase in soil nutrient levels and organic matter but may also risk nutrient leaching if not appropriately managed. Farmyard manure positively affects plant growth and yield, particularly in nutrient-poor soils (Ahlawat et al., 2023). Biochar is known for improving soil physical properties (Blanco-Canqui, 2021; Botková et al., 2023), including soil structure (Juriga and Šimanský, 2018; Juriga et al., 2021; Šimanský, 2016; Šimanský et al., 2022), increasing nutrient retention (Ng et al., 2023), and enhancing microbial habitats (Lehmann et al., 2011). It can play a role in carbon sequestration (Šimanský et al., 2018; Šrank and Šimanský, 2020) and water retention (Balashov et al., 2021). It may improve soil pH (Horák, 2015) and increase cation exchange capacity (Igaz et al., 2018), which improves nutrient availability (Lehmann and Joseph, 2015). Some studies suggest biochar can enhance crop yields (Šimanský et al., 2019), particularly in acidic soils, by improving nutrient availability (Igaz et al., 2018; Jeffery et al., 2011). Combinations of the above-mentioned organic amendments with biochar can maximize each of their benefits in the best way. Of course, due to the great complexity of the soil environment, the effect may not be so clear or even negative. The incorporation of these organic materials into soils can lead to nutrient imbalances, particularly when the components are combined in inappropriate ratios, especially without knowledge of their initial composition and properties, then it can result in some problems. For example, a high content of nitrogen and phosphorus in all input materials and their improper ratio can result (after its incorporation to the soil) in excessive runoff of these elements from the final product into waterways, contributing to eutrophication (Wang et al., 2018). Furthermore, manure and digestate can introduce pathogens and contaminants, such as heavy metals, into the soil (Mao et al., 2019). While biochar has been touted for its ability to mitigate some of these issues by retaining nutrients and reducing leachability, care must be taken to select the right feedstock and production conditions, as poor-quality biochar can increase soil contamination and hinder plant growth (Jeffery et al., 2011). Only feedstocks that do not contain high concentrations of harmful substances should be used for the production of biochar, as these substances are likely to appear in the final biochar. From the perspective of the input feedstocks used and the production process itself, it is essential that the final biochar has the most optimal properties possible. The final biochar should not immobilize nutrients that are necessary for the healthy growth of plants. For this reason, biochar producers pay increased attention to this issue and improve the final biochar through activation (Usman et al., 2015) and biochar coating or surface modification (Jia et al., 2015; Smith et al., 2016). By mixing high-quality organic materials and modified biochar, biochar substrate producers ensure a high-

quality final product. Understanding these potential drawbacks is crucial for fostering sustainable practices and ensuring the long-term health of our ecosystems.

Biochar blending with organic fertilizers, such as sheep manure, and residues from a biogas station such as digestate, has emerged as a possible solution to optimize the biochar potential as a soil amendment. Incorporating these organic materials into soils can improve nutrient profiles and mitigate the adverse effects of pure biochar applications (Angin et al., 2020). By varying the ratios of biochar, sheep manure, and digestate, the synergistic effects of these materials on soil properties can be explored, which may lead to more tailored and effective soil management strategies. In this study, the impact of biochar blended with sheep manure and digestate in different ratios on soil parameters was evaluated. Our study aimed to improve the understanding of the interplay between these components and their overall effect on soil health, providing insights into more sustainable agricultural practices that can enhance soil quality while contributing to carbon sequestration efforts. We hypothesize that (1) the difference in soil amendments can have a significant effect on the tested soil and plant parameters, (2) the impact of soil amendment treatments on plant growth parameters can change significantly over time, indicating that time is an important factor, and (3) the treatment of biochar mixed with sheep manure in 50:50 ratio can exhibit the most significant changes in the tested parameters, however, it does not have to be the best treatment for soil environment and plant growth.

MATERIAL AND METHODS

Experimental design

The leaching experiment was conducted in sand columns (1.0 kg of silica sand) placed in 1.5L polyethylene terephthalate (PET) bottles. The tested soil amendments were put on the sand and then incorporated into the sand max. to the depth of 10 cm, and the columns were subsequently placed in the custom-designed leaching apparatus (Fig. 1). The tested soil amendments included compost and three Biochar Substrates (BSs). The rate of the soil amendments was set at 1% of the total volume of each column because Major (2013) reported that application rates less than or about 1% could successfully promote crop yield. Each sand column was subjected to a regular leaching regime, which involved the application of 150 ml of distilled water per column at predefined intervals. A total of 16 irrigation cycles were performed throughout the workweek (Monday to Friday). The leachate that passed through the sand was collected for subsequent analysis. The experiment took place at a temperature of 20–22 °C.



Fig. 1. Setup of the leaching experiment.

Characteristics of soil amendments

A detailed description of the tested soil amendments is summarized in Table 1. Biochar Substrates (BS): the biochar substrates were under the trademark Effeco and consisted of various mixtures of biochar produced from pyrolyzed hardwood at 500°C, dried sheep manure, and residues from a biogas station (originally sourced from cattle manure). All the products studied in this experiment had concentrations of heavy metals that did not exceed the permissible limits established by the Slovak regulation 577/2005. Each biochar substrate for better application to the soil and manipulation was granulated into pellets measuring approximately 2 cm × 1 cm × 1 cm. The compost was not pelleted. It was in the form of a homogenized mass.

Table 1. Properties of the used soil amendments.

Soil amendments	Organic carbon in %	pH	Description
Compost	47.0	8.20	Organic waste biomass consisting of mown grass, pruned tree and shrub branches, and fallen leaves.
Biochar Substrate 1 (BS1)	43.0	8.18	Biochar and dried sheep manure in 50:50 ratio.
Biochar Substrate 2 (BS2)	45.4	8.44	Biochar, dried sheep manure, and biogas station residue (digestate) in 33:33:33 ratio.
Biochar Substrate 3 (BS3)	48.9	8.70	Biochar, dried sheep manure, and biogas station residue (digestate) in 30:50:20 ratio.

Laboratory analysis

The pH of the tested soil amendments was determined potentiometrically using a pH meter (HANNA instruments HI 2211), while the electrical conductivity (EC) was measured by a conductor (DiST HANA HI 9831). The concentration of water-soluble salts in the leachates was determined by weighing the dry residue after evaporation of the leachate. The leachate was evaporated using a water bath in a weighed porcelain bowl. Before its complete evaporation, 2 ml of 20% H₂O₂ was added and evaporated to dryness. The residue was dried at 105 °C. The percentage of water-soluble salts was calculated according to Hrivňáková et al. (2011). In the extracts, the chloride content (Cl⁻) was also determined through titration with 0.1 M AgNO₃ in a neutral pH using K₂CrO₄ as an indicator (Hrivňáková et al., 2011). The following organic substances were determined in the leachate dry material: the cold-water-soluble carbon (CCWD) content was determined using wet combustion – oxidation of organic matter by a mixture of H₂SO₄ and K₂Cr₂O₇ with residue titrated with Mohr's salt (Dziadowiec and Gonet, 1999); the composition of humic acids (HA) and fulvic acids (FA) was determined according to the Belchikova and Kononova procedure (Dziadowiec and Gonet, 1999).

Statistical analysis

A two-way ANOVA with repeated measures was used to analyze the data to determine statistically significant differences between the soil amendment treatments over the time and to evaluate the impact of these treatments on the studied soil parameters. This method allows to assess the main effects of the treatments and time, as well as their interaction effect on the soil parameters. The soil parameters examined included pH, EC, CCWD, Cl⁻, HS, HA, FA, and water-soluble salts while accounting for repeated measurements on the same parameters where measurements were taken at multiple time points. In the analysis, the null hypothesis was that factor A (Treatment): compost, BS1, BS2, BS3 and Factor B (irrigation cycle): date 1, date 2, and date 3 do not influence the dependent variables pH, EC, CCWD, Cl⁻, HS, HA, FA, and water-soluble salts. This study also investigated the interactions between the soil chemical parameters under different treatments. A principal component analysis (PCA) was used. PCA is a statistical technique used to reduce the dimensionality of a dataset while preserving as much variance as possible. It transforms the original variables into a new set of uncorrelated variables called principal components (PCs). Each principal component is a linear combination of the original variables, which are orthogonal. All the calculations were done using Statistica software (TIBCO Software Inc. Statistica, Data Analysis Software System; Version 13; TIBCO Software Inc.: Palo Alto, CA, USA, 2017.) with a significance level of 0.05.

RESULTS AND DISCUSSION

Effect of the treatments on physico-chemical parameters

The data derived from our study show the dynamic interactions between the treatments studied and the investigated parameters over a defined time frame (Fig. 2A–D), reflecting the intricate processes occurring in soil chemistry and biology. These results can be very useful in predicting the effect of individual soil amendments used in different soil-climatic conditions worldwide. The leachates from the soil treated with compost, BS1, BS2, and BS3 had a pH range of 6.1–7.2, 6.05–7.05, 5.55–7.06, and 5.61–7.1, respectively. For the individual treatments, the dynamics of changes in the leachate pH were different. As a rule, it increased from lower initial values, was the highest after 8 irrigation cycles for all the treatments, and then gradually decreased again (Fig. 2A). However, in the case of all the BS treatments, the pH of the leachates did not drop below the initial pH level, as was found in the case of the compost treatment. Fertile soil has a pH range of 5.6–8.2 (Šimanský et al., 2023). Soil organisms also have specific requirements for soil pH, while its optimum range depends on the individual species of soil microorganisms or their specific groups (Graham et al., 1994; Zifcakova, 2020). For most cultivated plants, the optimum soil pH is 5.5–6.5 (Kováčik and Ryant, 2024), but the most optimal conditions for plant nutrient uptake is about pH 6.5 (Fecenko and Ložek, 2000). The relatively stable pH across the soil amendment treatments suggests minor fluctuations, yet the pH values generally stay within the optimal range for microbial activity and nutrient availability. This stability may enhance the resilience of soil ecosystems to anthropogenic or environmental disturbances (Ritchie and Dolling, 1985). Overall, there were statistically ($p < 0.05$) significant differences in the average leachate pH between compost and the BS treatments (Table 2). This finding is consistent with the previous research results (Horák, 2015; Yan et al., 1996; Yuan et al., 2011) indicating that various treatments, such as soil amendments or chemical fertilizers, can lead to shifts in pH due to alterations in the availability of hydrogen

Table 2. The results of a two-way ANOVA with repeated measures analysis, means and standard deviations (SD) of the studied leachate parameters for the studied treatments.

	pH	EC	Water-soluble salts	Cl ⁻
		mS m ⁻¹	%	%
Treatment	0.003	0.04	<0.001	0.57
Irrigation cycle	<0.001	<0.001	<0.001	0.01
Compost	6.72 ± 0.30 b	240 ± 220 ab	0.03 ± 0.02 a	0.03 ± 0.02 a
BS1	6.52 ± 0.29 a	333 ± 197 b	0.08 ± 0.05 c	0.04 ± 0.02 a
BS2	6.39 ± 0.40 a	256 ± 124 ab	0.03 ± 0.01 ab	0.03 ± 0.01 a
BS3	6.43 ± 0.41 a	226 ± 106 a	0.02 ± 0.01 a	0.03 ± 0.01 a

EC - electrical conductivity, Cl⁻ - chloride ions.

The same letters in the columns mean the same homogenous group according to Tukey's procedure.

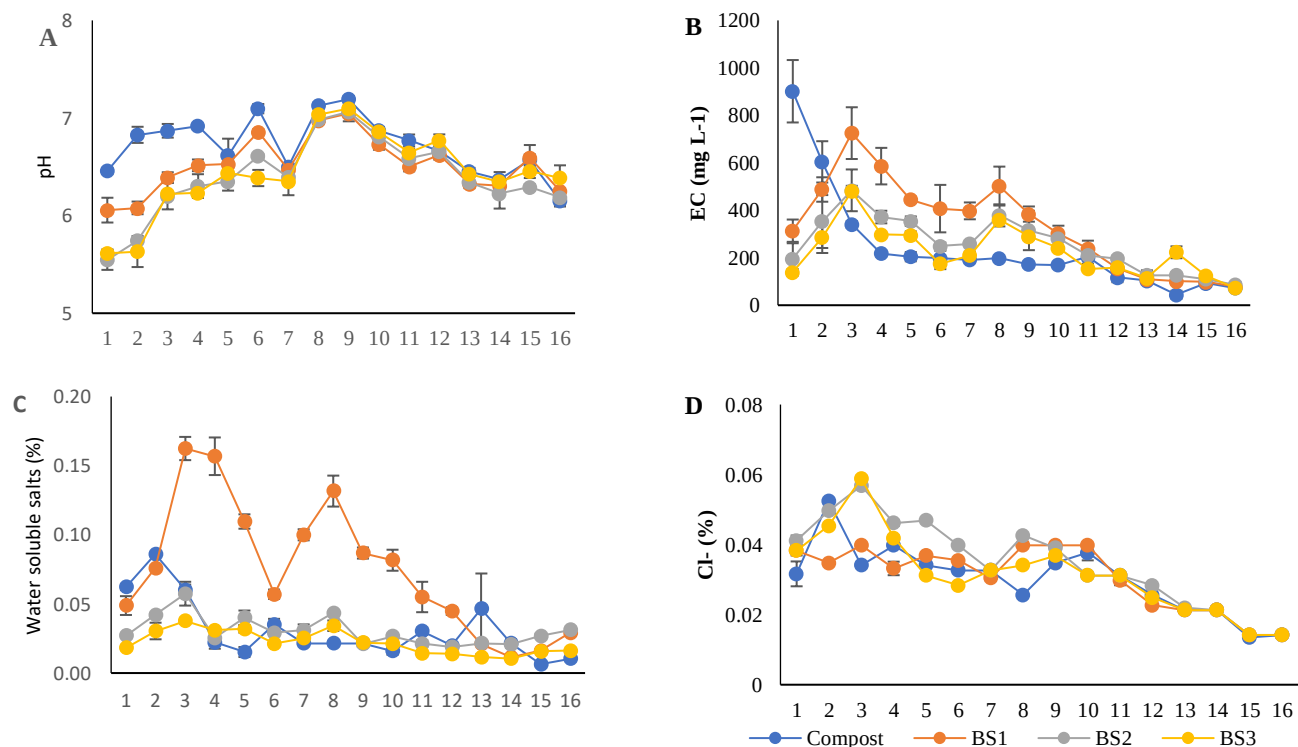


Fig. 2. Changes in the leachate parameters: (A – pH, B – Electric conductivity, C – Content of water-soluble salts, D – Content of chlorite ions) over time (from 1st to 16th irrigation cycle) for different treatments: Compost, BS1, BS2, BS3.

ions and nutrient dynamics. However, the reaction in individual soil types may differ slightly depending on the soil buffering capacity (Hanes, 1999).

Electrical conductivity (EC) values provide crucial insight into the salinity of the treated soil. Leachate of the compost demonstrated a steady decrease in EC from 902 mS m⁻¹ after 1st irrigation cycle to 72 mS m⁻¹ at the end of the investigation (after 16 irrigation cycles), which was consistent with the expectations. However, the results for the leachates from the BSs treatments were different. Changes in EC were about the same at the end of all the irrigation cycles but two peaks with the highest EC values were observed – after the 3rd and the 8th irrigation cycles. The changes can be attributed to several factors, such as the salt content in biochar substrates, which are released during the initial irrigation cycles. These salts can cause temporary spikes in EC as they leach out of the biochar or fluctuations can also be caused by the different leaching rates of individual salts in the biochar (Gabhi et al., 2020). The physical and chemical properties of biochar, such as porosity and surface area, can affect its interaction with water, influencing cation exchange and nutrient release (Chacón et al., 2017; Igaz et al., 2018). Based on the peak height the treatments

can be put in the following order: BS1 > BS2 > BS3 (Fig. 2B). Statistically significant ($p < 0.05$) differences in the mean EC values were found only between BS1 and BS3 treatments (Table 2). Such differences could be linked to the different ionic compositions of the soil amendments studied in the experiment, which can either contribute to or mitigate salinity levels (Jones a Brown, 2020). A high salt concentration above 1600 mS m⁻¹, a range of 800–1600, 400–800, 200–400, and under 200 mS m⁻¹ represents strong salinization, moderate salinity, weak salinity, negligible salinity, and no salinity, respectively (Hanes, 1999). Overall, the measured EC values did not reach the critical level for any of the tested soil amendments so their potential application to the soils does not pose a risk of stressful conditions for cultivated plants and soil microorganisms (Ratzke and Gore, 2019). The total mineralization of the leachates from the soil with the studied treatments did not exceed the critical level of 0.3% (Šimanský et al., 2023) and was the highest – 0.08% – in the BS1 treatment and the lowest – 0.02% – in the BS3 treatment (Table 2). The chlorine issue is given marginal attention in literature, while its negative effects are emphasized above all. Chlorine, however, also has its positive effects because when it is rationally present in the air, soil,

and in the plant, it helps plants to better tolerate any stressful conditions that arise during various plant diseases and thus ultimately eliminates the negative impact on the overall crop yield (Kováčik and Ryant, 2024). The chloride (Cl^-) concentration in the leachates under the compost treatment reflected a mild and steady decline, likely indicative of improved nutrient retention and lower leachate losses due to organic material being added (Havlin et al., 2017; Kováčik and Ryant, 2024). Conversely, while BS2 and BS3 treatments also demonstrated decreasing trends in Cl^- content in the leachates, the initially higher Cl^- concentrations indicate an oxidizable state of the organic material that may reflect the formulation's salt content or mineral composition influencing solubility. The dramatic fluctuations in Cl^- content observed in BS1 can be attributed to the higher organic matter content, which can initially drive Cl^- concentrations up before their leaching (Fig. 2D). Lastly, Cl^- content in the leachates under the studied treatments is not a problem as no significant increase in free chlorine content was observed across the tested soil amendments (Table 2). This finding suggests that the substrates may not pose a risk of chlorine toxicity to plants, which is essential for

maintaining plant health, especially in sensitive species (Kováčik and Ryant, 2024). Interestingly, the lack of significant differences across the treatments for chloride ion concentrations suggests a resilience in these parameters to manipulation via the treatments employed. This might imply that while certain treatments can lead to focal changes in pH, and EC, they may not equally influence chloride levels or factors that may require more intensive or specific interventions to induce change.

Effect of organic amendments on the content of organic matter fractions

The compost treatment demonstrated a marked reduction in cold-water-soluble carbon (CCWD) content, which declined from 2531 mg L^{-1} after 1st irrigation cycle to 359 mg L^{-1} after the last (16th) irrigation cycle. This reduction could be attributed primarily to the rapid dissolving of the very labile components of the organic matter contained in the compost (Shein et al., 2001).

Table 3. The results of a two-way ANOVA with repeated measures analysis, means and standard deviations (SD) of the studied organic matter substances in leachates under studied treatments.

	CCWD mg L^{-1}	HS %	HA %	FA %
Treatment	<0.001	<0.001	0.28	<0.001
Irrigation cycle	<0.001	0.03	0.03	0.14
Compost	1101 $\pm$ 713 a	0.18 $\pm$ 0.08 a	0.08 $\pm$ 0.04 a	0.10 $\pm$ 0.05 a
BS1	4606 $\pm$ 2 775 c	0.47 $\pm$ 0.23 b	0.08 $\pm$ 0.04 a	0.39 $\pm$ 0.22 a
BS2	1463 $\pm$ 747 b	0.18 $\pm$ 0.06 a	0.07 $\pm$ 0.02 a	0.11 $\pm$ 0.05 a
BS3	1134 $\pm$ 599 a	0.15 $\pm$ 0.05 a	0.06 $\pm$ 0.02 a	0.08 $\pm$ 0.03 a

CCWD – cold-water-soluble carbon, HS - humic substances, HA - humic acids, FA - fulvic acids.

The same letters in the columns mean the same homogenous group according to Tukey's procedure.

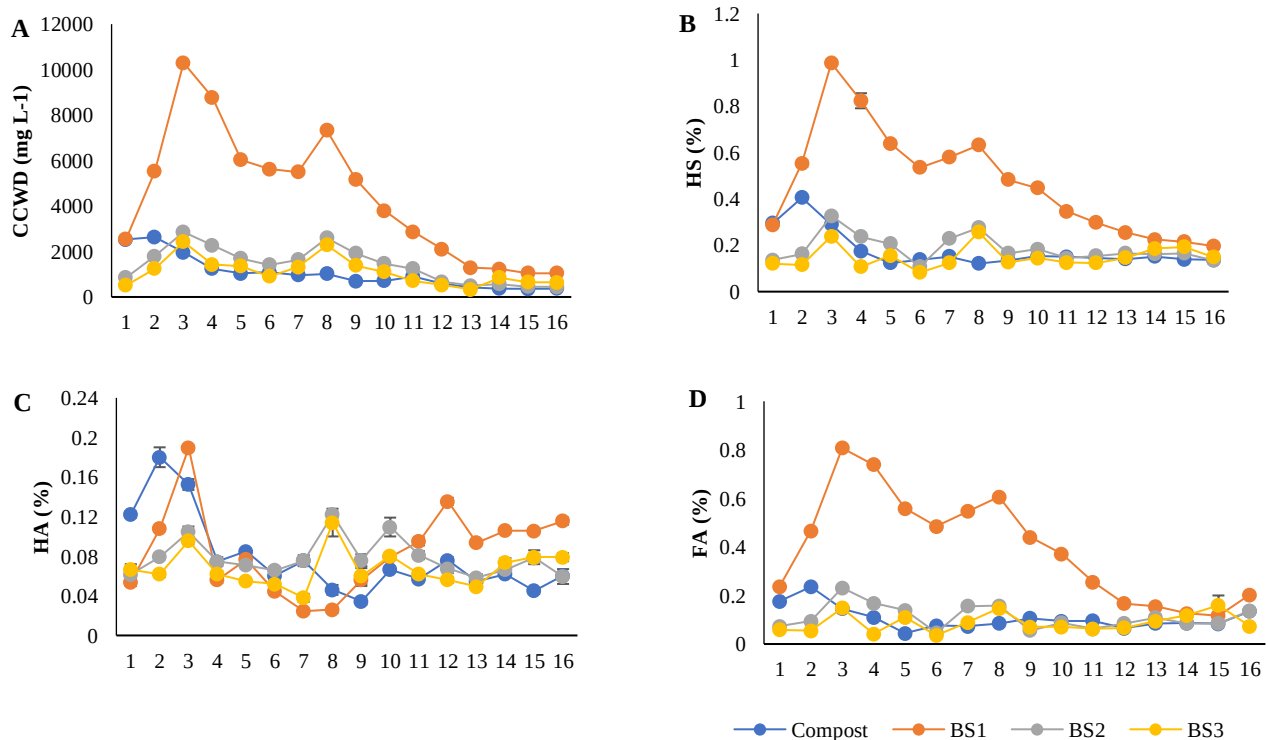


Fig. 3. Changes in the contents of (A) cold-water-soluble carbon, (B) humic substances, (C) humic acids, and (D) fulvic acids) over time (from 1st to last 16th irrigation cycle) for different treatments: Compost, BS1, BS2, BS3.

Furthermore, the analysis of CCWD content in the leachates showed that BS1 had the highest concentration, followed by BS2 > BS3, and compost (Table 3). The higher levels of CCWD content under the BS1 treatment suggest a higher content of very labile organic matter in this material composition and a greater potential for nutrient release. That could make BS1 more advantageous for more nutrient-demanding plant cultivation than the other tested amendments. These findings showed that biochar substrates with different biochar ratios to other components were an important source of easily accessible organic matter, which can be an available substrate for soil microorganisms after their incorporation into the soil. However, several studies state that biochar is a stable source of organic carbon based on its high aromaticity and degree of condensation (Gupta and Germida, 2015). The observed differences in CCWD content between compost and biochar treatments can be explained by the inherent properties of biochar. Biochar's high surface area and porosity enhance its ability to retain and slowly release nutrients, which can lead to higher initial leaching of labile organic matter followed by a more gradual release (Meng et al., 2021).

The extraction of humic substances (HS), including humic (HA) and fulvic acids (FA), from leachates under the studied treatments yielded significant results. BS1 exhibited the highest content of humic substances compared to the other treatments (Table 3) also their dynamics after irrigation cycles (Fig. 3B–D). Humic substances are known to improve soil structure, enhance nutrient availability, and stimulate microbial activity, which are all critical factors for soil health and plant growth (Weber, 2020). FA values for the different treatments also underline the variability that indicates differences in organic matter composition between the studied soil amendments. BS3 showed more stability, suggesting a more consistent organic structure than the other soil amendments. The relatively lower FA values in BS3 could also reflect lower mineralization rates or more stable organic structures in the future (after incorporation into the soil), potentially influencing nutrient availability over time (Simeonov et al., 2010). The predominance of HS in BS1 compared to the other soil amendments (Table 3) could be a key factor in its efficacy as a growth substrate.

Relationships between investigated parameters for different treatments

The analysis presented here utilizes Principal Component Analysis (PCA) to elucidate the relationships and variances within a dataset comprising different treatment conditions: compost, BS1, BS2, and BS3 (Fig. 4). Notably, the first two principal components (PC1 and PC2) account for an impressive 97% of the total variance, suggesting that much of the complexity of the original dataset can be effectively distilled into these two dimensions (Jolliffe and Cadima, 2016). PC1, which accounts for 83% of the variance, is predominantly influenced by EC, CCWD, Cl^- , FA, water-soluble salts, and HS. The high loadings of these variables along this axis affirm their collective capacity to explain significant variation between the treatments. Such findings are consistent with previous research indicating that these parameters are critical indicators of soil quality and fertility (Birk et al., 2017; Shah and Shukla, 2020). The strong inter-correlation among these factors highlights the interconnected nature of soil salinity and nutrient availability, which have profound implications for soil health and plant growth. In contrast, PC2, which accounts for 14% of the variance, reveals pH and HA as notable contributors. The unique positioning of the compost treatment in the upper right part of

the PCA graph indicates its distinct chemistry, characterized primarily by higher pH levels. This positioning suggests that compost treatment alters chemical properties favorably compared to the BS treatments.

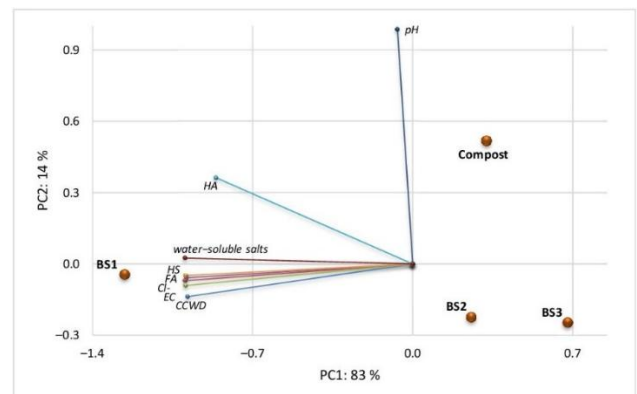


Fig. 4. PCA biplot illustrating the relationships between studied physico-chemical parameters and organic matter parameters (pH, EC, CCWD, Cl^- , HS, HA, FA, and water-soluble salts) of organic amendments leachates and their variation under four different treatments (Compost, BS1, BS2, BS3).

The placement of the BS1 treatment on the lefthand side of the figure reflected a strong correlation with high values of EC, CCWD, Cl^- , FA, and HS, which implies that this treatment may be more detrimental to soil health given the salinity-related plant stress that can arise from such high values. However, this relationship should be seen as a potential assuming very high values, especially pH, EC, salt content, and Cl^- -content, which was not observed in this study (Table 2, Fig. 2A–D). In contrast, BS2 and BS3 are clustered closer to the center, indicating that these treatments resemble each other more closely regarding their properties. This similarity could suggest potential redundancy in their efficacy, warranting further investigation into whether these treatments can be optimized for better soil health outcomes. Furthermore, the negative association of HA with PC1 suggests a unique behavior compared to the other variables, potentially indicating the varying roles of different organic matter fractions (Kumar et al., 2019). HA positive loading on PC2 might highlight its role in soil buffering capacity, particularly in relation to pH levels (Hanes, 1999).

CONCLUSIONS

The blending of biochar with organic components, particularly sheep manure and digestate, presents a promising strategy for soil health and fertility optimization. Our findings demonstrate that varying the ratios of these components in the soil amendments can significantly influence important soil parameters, such as pH, salinity, and the content of humic substances. While the incorporation of biochar enhances nutrient retention, careful consideration of the specific feedstocks and their interactions is crucial to mitigate potential nutrient imbalances and environmental risks. Overall, this study underscores the value of developing biochar-based substrates tailored to diverse agricultural needs, facilitating sustainable practices that support enhanced crop yields and environmental stewardship.

The results of this study indicated that, above all, biochar with sheep manure in a 50:50 ratio has the greatest potential to influence the measured parameters compared to the other tested substrates, which had more balanced dynamics of the observed

parameters for the investigated period, provided that the detected characteristics do not exceed the maximum permissible limits. In other words, when applying such substances to soils, it is extremely important to pay attention to reducing the application rate below 1% in order to avoid possible salinity-related plant stress.

Further research is needed to explore the long-term impacts of these amendments in various soil types and climatic conditions, ultimately contributing to the optimization of biochar agronomic benefits in the context of global sustainability efforts.

Acknowledgements. The research was partially supported by the Slovak Research and Development Agency under the contract No. APVV-21-00890, and the Slovak Grant Agency (VEGA) project no. 1/0116/21. N. Buchkina was partly working according to the scientific topic of the Agrophysical Research Institute.

REFERENCES

- Ahlawat, V., Dadarwal, R.S., Yadav, P.K., Chaudhary, K., 2023. Effects of long-term nutrient management practices on physicochemical properties of soils: A review. *Pharm. Innov. J.*, 12, 491–496.
- Angin, I., Kuru, M., Erinc, F., 2020. The effect of biochar amendment on soil properties and tomato yield. *Sustain. Agric. Res.*, 9, 94–104.
- Are, K.S., 2019. Biochar and soils physical health. In: Abrol, V., Sharma, P. (Eds.): *An Imperative Amendment for Soil and the Environment*. IntechOpen, Rijeka, Croatia, pp. 21–33.
- Balashov, E., Buchkina, N., Šimanský, V., Horák, J., 2021. Effects of slow and fast pyrolysis biochar on N₂O emissions and water availability of sandy and clayey loam soils with high water-filled pore space. *J. Hydrol. Hydromech.*, 69, 467–474.
- Birk, J.J., de Goede, R.G.M., Schouten, J., 2017. Indicators of soil quality: Effects of management practices. *Agr. Ecosyst. Environ.*, 241, 39–48.
- Blanco-Canqui, H., 2021. Does biochar application alleviate soil compaction? Review and data synthesis. *Geoderma*, 404, 115317.
- Botková, N., Vitková, J., Šurda, P., Massas, I., Zafeiriou, I., Gaduš, J., Rodrigues, F.C., Borges, P.F.S., 2023. Impact of biochar particle size and feedstock type on hydro-physical properties of sandy soil. *J. Hydrol. Hydromech.*, 71, 345–355.
- Cao, X., Ma, L., Harris, W., 2017. The effect of different types of biochar on agricultural productivity. *Agron. J.*, 109, 2922–2932.
- Chacón, F.J., Cayuela, M.L., Roig, A., Sánchez-Monedro, M.A., 2017. Understanding, measuring and tuning the electrochemical properties of biochar for environmental applications. *Rev. Environ. Sci. Biotechnol.*, 16, 695–715.
- Fecenko, J., Ložek, O., 2000. Nutrition and Fertilization of Field Crops. SAU, Nitra, Slovakia, 442 p. (In Slovak).
- Gabhi, R., Basile, L., Kirk, D.W., Giorcelli, M., Tagliaferro, A., Jia, Ch.Q., 2020. Electrical conductivity of wood biochar monoliths and its dependence on pyrolysis temperature. *Biochar*, 2, 369–378.
- García, M., Ocampo, J.A., Patiño, M., 2018. Effects of organic amendments on soil quality and the yield of several crops. *Agron. J.*, 110, 1158–1167.
- Githinji, L., Karanja, N., Kinyua, M., 2020. Biochar for improved soil health and crop production: A review. *J. Soil Sci. Plant Nut.*, 20, 1–22.
- Graham, P.H., Draeger, K.J., Ferrey, M.L., Conroy, M.J., Hammer, B.E., Martinez, E., Aarons, S.R., Quinto, C., 1994. Acid pH tolerance in strains of *Rhizobium* and *Bradyrhizobium*, and initial studies on the basis for acid tolerance of *Rhizobium tropici* UMR1899. *Can. J. Microbiol.*, 40, 198–207.
- Gupta, V.V., Germida, J.J., 2015. Soil aggregation: influence on microbial biomass and implications for biological processes. *Soil Biol. Biochem.*, 80, A3–A9.
- Hanes, J., 1999. Analyzes of Sorptive Characteristics, SSCRI, Bratislava, Slovakia, 138 p. (In Slovak).
- Havlin, J.L., Beaton, J.D., Tisdale, S.L., Nelson, W.L., 2017. *Soil Fertility and Fertilizers: An Introduction to Nutrient Management*. Pearson, 520 p.
- Horák, J., 2015. Testing biochar as a possible way to ameliorate slightly acidic soil at the research field located in the Danubian Lowland. *Acta Hort. Regiotech.*, 18, 20–24.
- Horák, J., Šimanský, V., 2017. Effect of biochar on soil CO₂ production. *Acta Fytotech. Zootech.*, 20, 72–77.
- Horák, J., Šimanský, V., Aydin, E., Igaz, D., Buchkina, N., Balashov, E., 2020. Effects of biochar combined with N-fertilization on soil CO₂ emission, crop yields and relationships with soil properties. *Pol. J. Environ. Stud.*, 29, 5, 3597–3609.
- Hrivňáková, K., Makovníková, J., Barančíková, G., Bezák, P., Bezáková, Z., Dodok, R., Grečo, V., Chlpík, J., Kobza, J., Lištjak, M., Mališ, J., Piš, V., Schlosserová, J., Slávik, O., Styk, J., Širáň, M., 2011. Uniform Methods of Soil Analyses, VÚPOP, Bratislava, Slovakia, 112 p. (In Slovak).
- Igaz, D., Šimanský, V., Horák, J., Kondrová, E., Domanová, J., Rodný, M., Buchkina, N.P., 2018. Can a single dose of biochar affect selected soil physical and chemical characteristics? *J. Hydrol. Hydromech.*, 66, 421–428.
- Jeffery, S., Verheijen, F.G.A., van der Velde, M., Bastos, A.C., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agr. Ecosyst. Environ.*, 144, 175–187.
- Jia, X., Yuan, W., Ju, X., 2015. Short report: effects of biochar addition on manure composting and associated N₂O emissions. *J. Sustain. Bioenergy Syst.*, 5, 56–61.
- IBI, 2015. State of the biochar industry 2015, A snapshot of commercial activity in the biochar sector. In: IBI-STD-0.1-1, International Biochar Initiative, accessed at. IBI-State-of-the-Industry-2015-final.pdf, Accessed date: 30 November 2024.
- Jolliffe, I.T., Cadima, J., 2016. Principal component analysis: A review and recent developments. *Philos. T. R. Soc. A: Math. Phys. Eng. Sci.*, 374, 20150202.
- Jones, A., Brown, C., 2020. Soil salinity management: Implications for crop production. *Agric. Sci.*, 11, 314–324.
- Juriga, M., Aydin, E., Horák, J., Chlpík, J., Rizhiya, E.Y., Buchkina, N.P., Balashov, E.V., Šimanský, V., 2021. The Importance of initial application and reapplication of biochar in the context of soil structure improvement. *J. Hydrol. Hydromech.*, 69, 87–97.
- Juriga, M., Šimanský, V., 2018. Effect of biochar on soil structure – review. *Acta Fytotech. Zootech.*, 21, 11–19.
- Kováčik, P., Ryant, P., 2024. *Agrochemistry, Principles and Practice*. SPU, Nitra, Slovakia, 385 p. (In Slovak).
- Kumar, A., Mani, M., Tripathi, V., 2019. Effect of soil amendment with organic matter on the physical and chemical properties of soil. *J. Soil Sci. Plant Nut.*, 19, 557–580.
- Lehmann, J., Joseph, S., 2015. *Biochar for Environmental Management*. Routledge, Taylor & Francis Group, London, New York, 928 p.
- Lehmann, J., Rillig, M.C., Thies, J., Masiell, C.A., Hockaday,

- W.C., Crowley D., 2011. Biochar effects on soil biota, A review. *Soil Biol. Biochem.*, 43, 1812–1836.
- Major, J., 2013. Practical aspects of biochar application to tree crops. In: IBI Technical Bulletin. International Biochar Initiative, pp. 102.
- Mao, J., Liu, M., Xu, J., Wang, W., Chen, H., 2019. Effects of long-term application of manure and digestate on soil microbial communities. *Sci. Total Environ.*, 654, 832–841.
- Matsumoto, T., 2021. Biochar in sustainable agriculture: Assessment of types and applications. *Agric. Sci. Rev.*, 13, 45–58.
- Meng, L., Li, W., Zhang, S., Zhang, X., Zhao, Y., Chen, L., 2021. Improving sewage sludge compost process and quality by carbon sources addition. *Sci. Rep.*, 11, 1319.
- Ng, C.W.W., Touyon, L., Bordoloi, S., 2023. Influence of biochar on improving hydrological and nutrient status of two decomposed soils for yield of medicinal plant – *Pinellia ternata*. *J. Hydrol. Hydromech.*, 71, 156–168.
- Ratzke, C., Gore, J., 2019. Modifying and reacting to the environmental pH can drive bacterial interactions. *PLoS Biol.*, 16, e2004248.
- Ritchie, G.S.P., Dolling, P.J., 1985. The role of organic matter in soil acidification. *Aust. J. Soil Res.*, 23, 569–576.
- Rončák, P., Némětová, Z., Vitková, J., Danáčová, M., Toková, L., Aydin, E., Valent, P., Honek, D., Igaz, D., 2023. Effects of the application of biochar on the soil erosion of plots of sloping agricultural and with silt loam soil. *J. Hydrol. Hydromech.*, 71, 356–368.
- Schmidt, H.P., Wilk, N., 2019. Effects of biochar on soil properties and plant growth: A review. *Plant Soil*, 442, 297–311.
- Shackley, S., Ruysschaert, G., Zwart, K., Glaser, B., 2016. *Biochar in European Soils and Agriculture, Science and Practice*. Routledge, London, New York, 301 p.
- Shah, S.A., Shukla, M.K., 2020. Exploring soil salinity: Implications for plant growth and ecosystem health. *Soil Sci. Soc. Am. J.*, 84, 1122–1140.
- Sharma, A., Soni, R., Soni, S.K., 2024. From waste to wealth: exploring modern composting innovations and compost valorization. *J. Mater. Cycles Waste Manag.*, 26, 20–48.
- Shen, Z., 2024. *Biochar Application in Soil to Immobilize Heavy Metals, Fundamentals and Case Studies*. Elsevier, Amsterdam, Netherlands, 252 p.
- Šimanský, V., 2016. Effects of biochar and biochar with nitrogen on soil organic matter and soil structure in Haplic Luvisol. *Acta Fytotech. Zootech.*, 19, 129–138.
- Šimanský, V., Aydin, E., Igaz, D., Horák, J., 2020. Potential application of biochar depends mainly on its profits for farmers: case study in Slovakia. *Agriculture*, 66, 171–176.
- Šimanský, V., Horák, J., Bordoloi, S., 2022. Improving the soil physical properties and relationships between soil properties in arable soils of contrasting texture enhancement using biochar substrates. *Geoderma Reg.*, 28, e443.
- Šimanský, V., Igaz, D., Horák, J., Šurda, P., Kolenčík, M., Buchkina, N.P., Uzarowicz, L., Juriga, M., Šrank, D., Pauková, Ž., 2018. Response of soil organic matter and water-stable aggregates to different biochar treatments including nitrogen fertilization. *J. Hydrol. Hydromech.*, 66, 429–436.
- Šimanský, V., Juriga, M., Golian, M., Šlosár, M., Provazník, M., 2021. Soil structure as a significant indirect factor affecting crop yields. *Acta Fytotech. Zootech.*, 24, 129–136.
- Šimanský, V., Polláková, N., Chlpík, J., Kolenčík, M., 2023. *Soil Science*. SPU, Nitra, Slovakia, 398 p. (In Slovak).
- Šimanský, V., Šrank, D., Juriga, M., 2019. Differences in soil properties and crop yields after application of biochar blended with farmyard manure in sandy and loamy soils. *Acta Fytotech. Zootech.*, 22, 21–25.
- Simeonov, L.S., Konstantinov, A.A., Petkov, P., 2010. The Role of organic matter in the movement of nutrients in soil. *Geoderma*, 154, 295–305.
- Smith, P., House, J.I., Bustamante, M., Sobocká, J., Harper, R., Pan, G., West, P.C., Clark, J.M., Adhya, T., Rumpel, C., Paustian, K., Kuikman, P., Cotrufo, M.F., Elliott, J.A., McDowell, R., Griffiths, R.I., Asakawa, S., Bondeau, A., Jain, A.K., Meersmans, J., Pugh, T.A.M., 2016. Global change pressures on soils from land use and management. *Glob. Chang. Biol.*, 22, 1008–1028.
- Šrank, D., Šimanský, V., 2020. Differences in soil organic matter and humus of sandy soil after application of biochar substrates and combination of biochar substrates with mineral fertilizers. *Acta Fytotech. Zootech.*, 23, 117–124.
- Usman, A.R., Ahmad, M., El-Mahrouky, M., Al-Omran, A., Ok, Y.S., Sallam, A.S., El-Naggar, A.H., Al-Wabel, M.I., 2015. Chemically modified biochar produced from conocarpus waste increases NO₃ removal from aqueous solutions. *Environ. Geochem. Health*, 38, 511–521.
- Wang, Y., Wang, J., Wang, J., Jiang, L., Liu, H., 2018. Effects of organic amendments on soil microbial activity and community structure. *Environ. Sci. Pollut. Res.*, 25, 10667–10678.
- Weber, J., 2020. Humic substances and their role in the environment. *EC Agric.*, 1, 3–8.
- Yan, F., Schubert, S., Mengel, K., 1996. Soil pH increase due to biological decarboxylation of organic anions. *Soil Biol. Biochem.*, 28, 617–624.
- Yuan, J., Xu, R., Qian, W., Wang, R., 2011. Comparison of the ameliorating effects on an acidic ultisol between four crop straws and their biochars. *J. Soil Sediment.*, 11, 741–750.
- Zifcakova, L., 2020. Factors affecting soil microbial processes. In: Datta, R., Meena, R.S., Pathan, S.I., Ceccherini, M.T. (Eds.): *Carbon and Nitrogen Cycling in Soil*. Springer, Berlin, pp. 439–461.

Received 7 October 2024
Accepted 4 December 2024