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ORIGINAL ARTICLE

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Assessing the long-term effect of different organic amendments on the quality of acidic sandy soil

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Abstract

Sandy soils are susceptible to the adverse effects of intensive land use and climate change, which can cause a decline in soil quality. As agricultural practices have an important role in soil processes, the objective of this research was to monitor the soil parameters determining the soil quality by studying the long-term effects of different organic amendments on soil. The research was done in long-term soil improvement experiments on Dystric Lamellic Arenosol. In addition to conventional organic fertilizers (farmyard manure with or without chemical fertilizers, green manure), alternative fertilizers such as sewage sludge compost were also applied. For the complex evaluation, we have been carrying out soil physical, chemical, and enzyme activity tests and field soil respiration measurements for 3 years. The beneficial effect of sewage sludge compost on the parameters determining the soil quality was more pronounced compared to the effect of conventional fertilization methods. The long-term incorporation of sewage sludge compost into the soil significantly increased the soil organic matter content and pH, and improved the physico-chemical parameters of the soil. The positive changes in soil parameters as a result of compost application contributed to the stimulation of soil life, which resulted in more intensive soil respiration and enzyme activities. The research confirmed the significance of the long-term supply of organic matter on sandy soil that can be implemented sustainably through the agricultural utilization of sewage sludge compost and contributes to the enhancement of soil organic carbon storage and the improvement of soil quality in acidic sandy soil.

1 | INTRODUCTION

The organic matter of the soil has an important role not only from the point of view of farming and ecology but also increasingly due to climate change. There is a significant potential to re-store large amounts of organic carbon in the soil, thereby improving soil quality and mitigating climate change (Amelung et al., 2020; Baveye et al., 2020).

Soil quality is considered the capacity of the soil to function within ecosystem and land use boundaries (Doran & Parkin, 1994). According to Chadwick et al. (2023), soil quality refers to the physical, chemical, and biological properties of soil, and it can be defined as "the ability of the

Abbreviations: BD, bulk density; DHA, dehydrogenase activity; FYM, farmyard manure; FYM + MF, farmyard manure + mineral fertilizer; GM, green manure; INV, invertase activity; SOM, soil organic matter content; SSC, sewage sludge compost; TP, total porosity.

soil to sustain the productivity, diversity, and environmental services of terrestrial ecosystems."

The Soil Strategy of European Union for 2030 defines a framework and specific measures to prevent land degradation, maintain the soil quality, and ensure the sustainable use of the soil. However, the organic matter content of European soils has significantly decreased in recent decades due to the soil degradation processes resulting from intensive land use and climate change (Borrelli et al., 2016; Crowther et al., 2016). Sandy soils occur in widely different environments in Europe, and their potential for agricultural use is variant (Šimanský et al., 2019). In the northeastern part of Hungary, most soils are generally dystrophic, acid, and sandy in texture, and they have low fertility and low nutrient-holding capacity. In addition, these acidic soils are characterized by rapid mineralization of organic matter. They are susceptible to compaction and have low water retention and high drainage, which can lead to nutrient leaching and water stress for plants (Aranyos et al., 2016).

Therefore, it is important to understand the mechanisms of carbon sequestration and apply the best management practices on sandy soils (Kravchenko et al., 2019). Fertilizers are not only an important factor in intensive crop production but also affect soil properties (Šimanský et al., 2019). Many agricultural practices such as crop rotation, by-products, and organic waste application can reduce and prevent land degradation (Abdalla et al., 2020). The use of locally available resources, such as composted solid wastes, treated wastewater, and industrial residues can help solve the problem of the organic matter supply of soils (Weber et al., 2014). In addition to sustainable management, the circular economy, waste reduction, and efficiency can also be ensured (Hernández-Chover et al., 2023).

The use of composted organic waste as organic fertilizer has been popular in agriculture for decades (Glab et al., 2018). Sewage sludge compost (SSC) contains considerable amounts of organic matter and essential nutrients for plants, so its agricultural application is considered an alternative for increasing the organic matter level of soil (Alvarenga et al., 2015). Land use of sewage sludge compost (SSC) improves soil resilience by increasing microbial activity, aggregate stability, and water-retention capacity (Abdalla et al., 2020). The application of SSC can result in higher soil organic carbon content due to stable organic substances that are more resistant to mineralization, thereby increasing the organic matter accumulation in the soil (Nicolás et al., 2012; Šimanský et al., 2019). The increase in soil carbon sequestration can be achieved by improving aggregation as well because the organic matter is trapped within the aggregates and thus protected from degradation (Grosbellet et al., 2011).

The amount of the soil organic carbon pool depends strongly on microorganisms, as microbial growth and activity balance the accumulation and mineralization of organic carbon in the soil (Liang et al., 2019). Microbiological parameters are more sensitive to environmental stress, and they are considered indicators of soil quality under various soil management and crop rotation systems (Franchini et al., 2007; Q. Zhang et al., 2015).

Core Ideas

- Long-term experiments provide valuable data on the effect of different organic amendments on soil processes.
- Sewage sludge compost treatment had a more favorable effect on the tested soil parameters than other amendments.
- Soil pH and organic matter content increased most significantly as a result of sewage sludge compost (SSC) treatment.
- The SSC application increased soil respiration and enzyme activity implying an increase in soil life.
- The use of SSC offers an alternative agricultural practice for improvement of acidic sandy soils.

Soil microbial activity is generally considered an important indicator of basal (actual) and potential microbial respiration (Romero-Freire et al., 2016). It can be well characterized by dynamic parameters such as enzyme activity and soil respiration. Soil enzymes are an essential part of the biogeochemical cycle of soil carbon because they play a significant role in the physical breakdown and biochemical transformation of organic matter (Ravn et al., 2020). Soil enzyme activity is considered a major factor in total soil microbial activity (Iovieno et al., 2009). The response of soil enzymes to both natural and anthropogenic factors is more rapid than other soil variables; therefore, soil enzymes have been considered sensitive early indicators of soil nutrient changes caused by climate change (C. Liu et al., 2021).

Soil respiration measurement is suitable for monitoring the decomposition of organic matter and for characterizing the microbiological activity of the soil (Luo & Zhou, 2006). In addition, organic matter decomposition is strongly influenced by applied agricultural systems; therefore, it is necessary to better understand the process of soil respiration and forecast the feedbacks of the soil to climate change (Franchini et al., 2007).

Long-term experiments are valuable resources for assessing the sustainability and resilience of agricultural practices and systems, and for monitoring the changes in soil parameters (Borase et al., 2020; Haddaway et al., 2016). Therefore, the aim of the research was to examine the long-term effects of different organic amendments, including by-products such as SSC, on physical, chemical, and microbiological parameters of the soil.

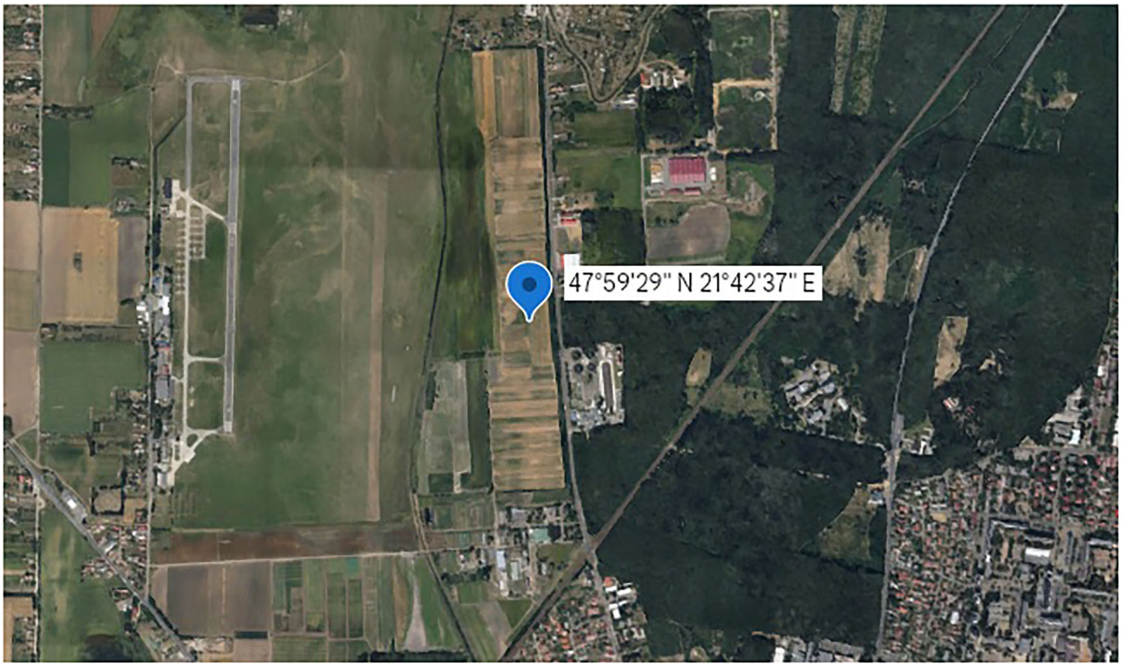

FIGURE 1 Location of the study area in Nyíregyháza, Hungary. *Source*: Google Earth 2024.

2 | MATERIALS AND METHODS

2.1 | Study area

The research was conducted between 2017 and 2019 in long-term soil improvement experiments (Westsik's Crop Rotation Experiment and Sewage Sludge Compost Experiment) at the Research Institute of Nyíregyháza, IAREF, University of Debrecen in Hungary. Westsik's crop rotation experiment was established in 1929 to study the effects of organic manure treatments and chemical fertilizers on soil properties and crop yields in different crop rotations. The same amendments have been carried out, and the same crops (rye—*Secale cereale* L., potato—*Solanum tuberosum* L., lupine—*Lupinus albus* L., oat—*Avena sativa* L.) with vetch (*Vicia sativa* L.) have been grown since the beginning of the experiment.

The SSC experiment was established in 2006 to study the effects of regular application of SSC on acidic sandy soil. Each plot is treated every third year with different doses (0, 9, 18, and 27 t ha^{-1}) of SSC. At the determination of the compost doses, the properties of compost and soil were considered.

The location (47°59′29″ N and 21°42′37″ E) of the experiments is shown in Figure 1.

The soil type of the study site is acidic (pH_{KCl} = 4.0) soil with a low SOM content (0.7%) and low nutrient supply (NO_2+NO_3-N: 3.8 mg kg^{-1}, available phosphorus: 32.1 mg kg^{-1}, available potassium: 59.8 mg kg^{-1}). The mechanical composition of the soil is as follows: 86.2% sand, 2.6% silt, and 9.6% clay. The typical soil type of the area is *Dystric Lamellic Arenosol* (Food and Agriculture Organization of the United Nations, 2015).

TABLE 1 Fertilization methods and fertilization doses in the investigated treatments (Nyíregyháza, Hungary).

	Mineral fertilizer (kg ha^{-1})			Organic fertilizer (t ha^{-1} DM)		
Treatment	**N**	**P**	**K**	**SSC**	**FYM**	**GM**
Control						
SSC				27.0		
FYM					26.1	
FYM + MF		13.5	23.2		26.1	
GM						20.0

Note: Phosphorus was added to soil in the form of superphosphate (8% phosphorus content, without calcium), and potassium was added to soil as potassium sulphate (25% potassium content).

Abbreviations: DM, dry matter; FYM + MF, farmyard manure + mineral fertilizer; FYM, farmyard manure; GM, green manure; K, potassium; N, nitrogen; P, phosphorus; SSC, sewage sludge compost.

The fertilization methods and fertilization doses in the investigated treatments are summarized in Table 1. This study focused on five fertilization treatments: fallow (as a control treatment), farmyard manure (FYM), farmyard manure + mineral fertilizer (FYM + MF), green manure (GM), and SSC. The fertilizers are applied every 3 years. During the study period, the treatments were done in the autumn of 2018. The measurements were taken in five replications in rye plots in 2017–2019. Lupine green manure was a cover crop, then plowed down. The biomass mass of green manure was

TABLE 2 The average values of the main properties of the applied organic fertilizers.

Parameter	Farmyard manure	Green manure	Sewage sludge compost
Nitrogen content (mg kg^{-1}, DM)	17,000	36,400	12,600
Total phosphorus (P) content (mg kg^{-1}, DM)	2545	637	4540
Total potassium (K) content (mg kg^{-1}, DM)	19,995	9790	22,402
Total organic carbon (TOC) (m/m%)	33.5	24.1	16.0
Dry matter content (m/m%)	33.2	ND	45.8
pH (H_2O) [–]	10.2	ND	7.1
C:N ratio [–]	34:1	11:1	22:1

Abbreviations: DM, dry matter; m/m%, mass/mass%; ND, not determined.

calculated based on plant samples collected from an area of 1 m^2 in four replications.

The SSC was made by adding straw, bentonite, and zeolite to the sewage sludge during the composting process. The average values of the parameters of the applied organic fertilizers are shown in Table 2.

2.2 | Weather data

The monthly amount of precipitation and the average air temperature data were measured between 2017 and 2019 by the weather station of the Research Institute of Nyíregyháza.

The average annual precipitation was 644 mm in 2017, 516 mm in 2018, and 626 mm in 2019. In the study period (May–July), the least amount of precipitation fell in 2018, while the most amount fell in 2019.

The mean temperature was 11.0˚C in 2017, 12.2˚C in 2018, and 12.0˚C in 2019. The average temperatures of 2018 and 2019 were higher than the long-term mean temperatures in the period from 1991 to 2019.

2.3 | Laboratory measurements

There were three sampling times between 2017 and 2019: before harvest (May 19, 2017, and June 28, 2018) and after harvest (July 22, 2019). Undisturbed soil samples with a volume of 100 cm^3 were collected from the 5- to 10-cm soil layer in five replicates for soil physical measurements. The bulk density of the soil is defined as the density of soil with pores measured after drying in an oven at 105˚C for 24 h (Buzás, 1993). The pore volume was determined by calculating the volume of water present in the saturated samples per unit of the dry weight (Buzás, 1993). Soil moisture content was determined by using the gravimetric method (Buzás, 1993).

For chemical and enzyme activity tests, composite soil samples were collected from the 0- to 25-cm soil layer in three replicates. Invertase activity (INV) was measured photometrically at 508 nm based on the glucose formation by the method of Mikanová et al. (2001). During the dehydrogenase activity (DHA) test, 2,3,5-triphenyl tetrazolium chloride (TTC) was used for incubation and the amount of generated triphenyl formazan (TPF) was measured by the photometric method (Casida et al., 1964).

The macro-, meso-, and microelements content of the soil was determined only in 2017 according to Hungarian standards. The potassium chloride (KCl) extracted nitrite-nitrate-N concentration was determined by the flow injection analysis (FIA) method using spectrophotometric detection (Buzás, 1988). Phosphorus and potassium were extracted from the soil by acidified ammonium lactate (AL) to determine plant available phosphorus and potassium content of the soil. The AL-soluble phosphorus content of the extract was measured by ultraviolet-visible (UV-VIS) spectrophotometry. The available potassium content was determined by flame atomic emission spectrophotometry (Buzás, 1988; Egner et al., 1960).

The 1 M KCl extractable magnesium (Mg) was determined by the inductively coupled plasma (ICP) Spectroscopy method. The soluble copper (Cu), zinc (Zn), and manganese (Mn) content of the soil was determined in the 0.1 M KCl + 0.05 M EDTA extractants by the ICP method (Buzás, 1988).

Soil pH_{KCl} was measured using the electrometric method in 1 M KCl suspension (Buzás, 1988). The soil organic matter content (SOM) was measured by the loss on ignition (LOI) method (Nelson & Sommers, 1996).

2.4 | Soil respiration measurement

Carbon dioxide emission related to soil biomass respiration was measured with an open system configuration of a soil chamber using a portable tool ADC LCi/LCpro soil pot (ADC BioScientific, 2007). Soil temperature (T_{soil}) was recorded simultaneously with the provided probe. CO_2 flux was measured by an infrared gas analyzer and soil respiration (R_s) was calculated by Net CO_2 Exchange Rate.

2.5 | Statistical analysis

The SPSS 22.0 program was used for the descriptive statistical analysis of the experimental data. Tukey's HSD (honestly significant difference) test was applied to identify the significant differences between the groups at the same time and the years at the significance level $p < 0.05$ in analysis of variance (ANOVA). Correlation analysis and multiple linear regression analysis were performed to describe and evaluate the relationship between soil parameters.

3 | RESULTS

3.1 | Soil chemical parameters

The chemical parameters of the soil are presented in Table 3. As expected, the organic matter content of the soil was highly responsive to different organic amendments. Generally, the lowest organic matter content was detected in control and GM (1.33%–1.55% and 1.35%–1.61%, respectively). The SSC treatment indicated the highest organic matter content of the soil (1.97-2.59%) at each sampling time. On average, a 20%–40% increase in SOM content can be observed as a result of the compost treatment compared to the other organic fertilizer treatments. The application of FYM and FYM + MF also contributed to a significant increase in soil organic matter content, except in 2018, while GM did not affect SOM in any year. Examining the annual effect on SOM, it can be seen that the lowest SOM content was generally measured in 2019 in all organic treatments.

At all three sampling times, the pH_{KCl} remained at the lowest level in the control and GM, which was close to pH 4. However, the FYM and FYM + MF significantly increased the soil pH_{KCl} in all investigated years. The beneficial effect of SSC on soil pH was distinctly shown. In this treatment, the highest pH value was observed at each sampling time. In comparison with the control, the SSC treatment resulted in an increase of more than 40% in soil pH. Examining the effect of the years on pH, it can be concluded that in 2019, a higher pH value was generally measured in the treatments than in the previous 2 years. There were not any interactions between treatment and time in ANOVA.

In 2017, the NO_3-NO_2-N content of the soil varied in the range from 1.8 to 5.9 mg kg^{-1} in the investigated treatments. The NO_3-NO_2-N content of the soil remained significantly lower in FYM than in other organic amendments. However, the application of GM and SSC contributed to a significant increase in nitrite-nitrate-N content of the soil.

Although there was no treatment effect on the available phosphorus content in GM, a considerable increase in available phosphorus content was observed in FYM, FYM + MF, and SSC. The phosphorus content of the soil was more than

TABLE 3 The chemical parameters of the soil (Nyíregyháza, Hungary).

Treatment	SOM (%)			pH (KCl)			NO_3-NO_2-N (mg kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})	KCl-soluble Mg (mg kg^{-1})	KCl-EDTA soluble Cu (mg kg^{-1})	KCl-EDTA soluble Zn (mg kg^{-1})	KCl-EDTA soluble Mn (mg kg^{-1})
	2017	2018	2019	2017	2018	2019	2017	2017	2017	2017	2017	2017	2017
Control	1.33 ± 0.03a,A	1.39 ± 0.13a,A	1.55 ± 0.02b,A	3.91 ± 0.04a,A	3.99 ± 0.02ab,B	3.95 ± 0.07a,AB	3.8 ± 0.2ab	32.1 ± 4.9a	59.8 ± 5.1a	38.2 ± 4.2ab	2.5 ± 0.4bc	0.5 ± 0.1a	56.0 ± 2.5b
SSC	2.45 ± 0.05e,AB	2.59 ± 0.32c,B	1.97 ± 0.07d,A	5.85 ± 0.15d,A	6.04 ± 0.28d,A	6.46 ± 0.09d,B	5.9 ± 1.1b	142.9 ± 11.7d	165.7 ± 18.6b	64.7 ± 5.0c	1.5 ± 0.2a	8.7 ± 0.8c	43.3 ± 7.3a
FYM	1.83 ± 0.09c,B	1.66 ± 0.09b,AB	1.53 ± 0.02b,A	4.75 ± 0.12c,A	4.99 ± 0.42c,AB	5.19 ± 0.09c,B	1.8 ± 0.9a	82.2 ± 3.2b	187.9 ± 17.1b	50.0 ± 5.4b	3.1 ± 0.3c	1.9 ± 0.2b	69.0 ± 1.7c
FYM + MF	1.95 ± 0.05d,B	1.71 ± 0.03b,A	1.79 ± 0.02c,A	4.31 ± 0.32b,A	4.27 ± 0.26b,A	4.37 ± 0.09b,A	4.1 ± 1.4ab	120.9 ± 6.5c	200.7 ± 21.7b	42.9 ± 6.3ab	3.0 ± 0.2c	1.5 ± 0.2ab	74.7 ± 0.8cd
GM	1.53 ± 0.03b,A	1.61 ± 0.34ab,A	1.35 ± 0.01a,A	3.84 ± 0.01a,A	3.85 ± 0.01a,A	3.91 ± 0.05a,B	4.5 ± 0.6b	25.2 ± 1.3a	77.5 ± 2.5a	31.5 ± 0.4a	2.2 ± 0.2b	0.5 ± 0.1a	80.2 ± 2.6d

Note: Small letters indicate significant differences between means of the treatments at the same time, while capital letters indicate significant differences between means of the treatments at different times (Tukey post hoc test; $p < 0.05$).

Abbreviations: EDTA, ethylenediaminetetraacetic acid; FYM, farmyard manure; FYM + MF, farmyard manure + mineral fertilizer; GM, green manure; KCl, potassium chloride; SSC, sewage sludge compost.

TABLE 4 Ranges of available phosphorus and potassium content of soil (Csathó, 2001).

Nutrient	Level	Value (mg kg^{-1})
Available phosphorus	Very low	<22
	Low	22–35
	Medium	35–52
	High	52–87
	Very high	87<
Available potassium	Very low	<50
	Low	50–75
	Medium	75–100
	High	100–150
	Very high	150<

five times higher in SSC compared to the control. According to the ranges of phosphorus content of the soil in Table 4, the available phosphorus content of soil remained at a low level in control and GM, and it was at a high level in SSC and a very high level in FYM and FYM + MF.

The potassium content of the soil varied similarly to the phosphorus content of the soil in the organic treatments. The GM had no significant impact on the available potassium content of the soil. However, the plant available amount of potassium was significantly raised above 165 mg kg^{-1} by FYM, FYM + MF, and SSC. Based on the data in Table 4, the available potassium content of soil was low in control and medium in GM. The soil of SSC, FYM, and FYM + MF contained very high amounts of available forms of potassium.

The meso- and microelement content of the soil changed differently according to the type of investigated element. The $CaCO_3$% was below the measurement limit (<0.1) in all treatments; thus, it is not presented.

The GM and FYM + MF treatments did not have any effect on the magnesium content of the soil. However, the FYM and SSC brought about a significant increase in the Mg content of the soil.

Control and GM contained the lowest available Zn content in the 0- to 25-cm soil layer. The FYM + MF had no pronounced effect on soil Zn content. The most appreciable increase in the Zn content of the soil was caused by SSC application. In addition, the amount of this microelement was also statistically higher in the soil treated with FYM. In contrast, the lowest copper and manganese contents of the soil were found in SSC, and the contents of these elements were significantly higher in the other examined treatments.

3.2 | Soil physical parameters

In the present study, the physical properties of the sandy soil of the 5- to 10-cm soil layer were significantly improved by all organic treatments in all 3 study years (Table 5). As expected, the application of all organic fertilizers contributed to a significant decrease in the bulk density of the soil during the 3 years. The total porosity of the soil varied according to the values of bulk density. In 2017 and 2018, the use of all organic fertilizers significantly enhanced the total volume of the pores in the soil. A similar conclusion can be drawn in 2019 as well, only the green manure treatment had no significant impact on the total porosity. The annual effect on bulk density and total porosity is not clear in the different treatments.

The influence of treatments was also reflected in the changes in soil temperature (Table 5). In 2017 and 2018, the soil temperature changed similarly in the various organic matter treatments. At the first two measurement dates, the highest soil temperature was observed in GM. In addition to the control, plots treated with SSC, FYM, and FYM + MF showed significantly lower soil temperatures compared to GM. At the third measurement date, the lowest soil temperature values were obtained in FYM and FYM + MF, while the control and SSC plots showed the highest soil temperature. Moreover, the effect of years on soil temperature was significant for all treatments. The highest soil temperature values were observed in 2018 and 2019.

At the first sampling time, the soil of each organic matter treatment retained significantly more moisture than the control soil. However, no clear conclusions can be drawn about the effects of different organic amendments on soil moisture in 2018 and 2019. At the second sampling time, the soil moisture content was significantly lower in FYM + MF and GM compared to the other treatments. In 2019, the soil of control, FYM + MF, and GM contained significantly more moisture than SSC and FYM treatments. The data clearly showed the significant effect of the years on soil moisture content. For all treatments, the lowest moisture contents were measured in 2017, and the highest moisture contents were detected in 2019.

There was no significant interaction between treatment and time on soil physical properties.

3.3 | Soil respiration

During the first two measurements, the application of SSC caused the greatest increase in the intensity of soil respiration. The rate of soil respiration raised more than twice as a result of SSC treatment in comparison with control. In 2017 and 2018, the FYM and FYM + MF treatments also had a significant effect on the amount of soil carbon dioxide emissions compared to the control. However, in 2019, the opposite of the previous measurement results was found, and the highest rate of soil respiration was measured in the control treatment. There were no significant differences among the other organic treatments during the last measurement (Figure 2). The effect

TABLE 5 The physical parameters of soil in different fertilization treatments in 2017–2019 (Nyíregyháza, Hungary), mean ± standard deviation (SD).

Year	Treatment	Bulk density (g cm^{-3})	Total porosity (V/V %)	Soil temperature (˚C)	Soil moisture content (VWC %)
2017	Control	1.52 ± 0.03b,A	42.92 ± 1.25a,A	17.9 ± 0.3b,A	4.6 ± 0.6a,A
	SSC	1.41 ± 0.02a,B	46.26 ± 0.90bc,A	17.4 ± 0.1a,A	7.8 ± 0.3c,A
	FYM	1.40 ± 0.04a,A	47.73 ± 0.85d,A	17.2 ± 0.3a,A	6.5 ± 0.2b,A
	FYM + MF	1.41 ± 0.01a,B	47.63 ± 0.54cd,A	17.3 ± 0.4a,A	6.7 ± 0.8b,A
	GM	1.42 ± 0.05a,A	45.66 ± 1.99b, AB	24.5 ± 0.3c,A	6.2 ± 0.4b,A
2018	Control	1.55 ± 0.02c,B	42.13 ± 0.46a,A	24.7 ± 0.2b,B	9.4 ± 0.3b,B
	SSC	1.42 ± 0.04b,B	46.19 ± 1.05b,A	24.9 ± 0.6b,B	9.1 ± 0.5b,B
	FYM	1.42 ± 0.01b,A	47.93 ± 0.53c,A	23.3 ± 0.5a,C	9.4 ± 1.0b,B
	FYM + MF	1.37 ± 0.04a,A	49.10 ± 1.39c,B	23.0 ± 0.1a,B	8.0 ± 1.0a,B
	GM	1.40 ± 0.02ab,A	46.49 ± 1.48b,B	27.1 ± 0.5c,C	8.0 ± 0.2a,B
2019	Control	1.50 ± 0.03d,A	43.11 ± 1.40a,A	27.9 ± 0.3c,C	12.6 ± 1.4b,C
	SSC	1.34 ± 0.02a,A	49.63 ± 0.73c,B	28.2 ± 0.3c,C	9.9 ± 0.7a,C
	FYM	1.40 ± 0.02bc,A	47.91 ± 0.70b,A	22.7 ± 0.7a,B	10.6 ± 0.5a,C
	FYM + MF	1.39 ± 0.02b, AB	47.12 ± 0.60b,A	23.8 ± 2.1a,C	13.5 ± 0.5b,C
	GM	1.44 ± 0.03c,A	43.91 ± 0.99a,A	25.1 ± 0.9b,A	11.1 ± 0.5b,C

Note: Small letters indicate significant differences between means of the treatments at the same time, while capital letters indicate significant differences between means of the treatments at different times (Tukey post hoc test; $p < 0.05$).
Abbreviations: FYM, farmyard manure; FYM + MF, farmyard manure + mineral fertilizer; GM, green manure; SSC, sewage sludge compost; VWC %, volumetric water content.

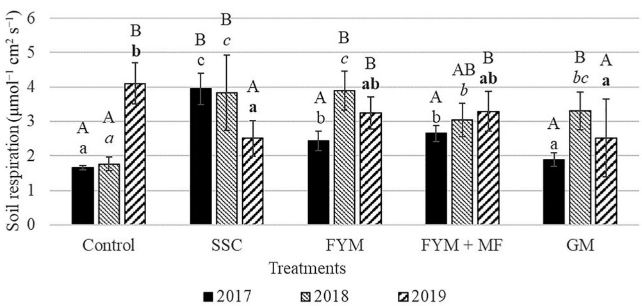

FIGURE 2 Results of soil respiration measurements in the field of long-term experiments in 2017–2019 (Nyíregyháza, Hungary), mean ± standard deviation (SD) *Note*: Small letters indicate significant differences between means of the treatments at the same time, while capital letters indicate significant differences between means of the treatments at different times (Tukey post hoc test; $p < 0.05$). FYM, farmyard manure; FYM + MF, farmyard manure + mineral fertilizer; GM, green manure; SSC, sewage sludge compost.

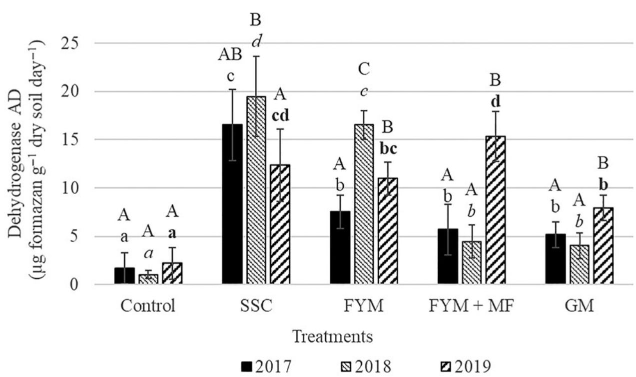

FIGURE 3 Changes in dehydrogenase activity in different fertilization treatments in long-term experiments in 2017–2019 (Nyíregyháza, Hungary), mean ± standard deviation (SD). *Note*: Small letters indicate significant differences between means of the treatments at the same time, while capital letters indicate significant differences between means of the treatments at different times (Tukey post hoc test; $p < 0.05$). AD, activity of dehydrogenase; FYM, farmyard manure; FYM + MF, farmyard manure + mineral fertilizer; GM, green manure; SSC, sewage sludge compost.

of the years on R_s was different for all treatments; therefore, no clear conclusion could be drawn.

3.4 | Enzyme activity

All applied organic fertilizers resulted in an appreciable increase in the enzyme activities of the sandy soil over the 3 years. The beneficial effect of SSC treatment on DHA was more pronounced compared to other organic treatments in all 3 years. In 2018, the activity of DHA was almost 20 times higher in SSC than in the control. The activity of DHA also increased significantly with the use of FYM, FYM + MF, and GM compared to the control at each sampling time (Figure 3).

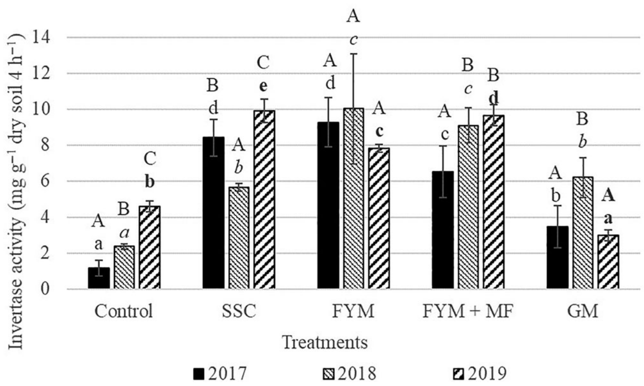

FIGURE 4 Changes in invertase activity in different fertilization treatments in long-term experiments in 2017–2019 (Nyíregyháza, Hungary), mean ± standard deviation (SD). *Note*: Small letters indicate significant differences between means of the treatments at the same time, while capital letters indicate significant differences between means of the treatments at different times (Tukey post hoc test; $p < 0.05$). FYM, farmyard manure; FYM + MF, farmyard manure + mineral fertilizer; GM, green manure; SSC, sewage sludge compost.

The positive effect of organic fertilizer treatments on soil INV was also clearly expressed between 2017 and 2019 (Figure 4). The most significant increase in INV could be observed in SSC, FYM, and FYM + MF treatments. In these treatments, —five to eight times higher INV was measured than in the control. The INV activity was also significantly affected by the application of GM, except in 2019.

There was an effect of the years on soil enzyme activities, but no consistent effect could be established for all treatments. There was no significant interaction between treatment and time on soil respiration and enzyme activities.

3.5 | Estimated marginal means, correlation, and multiple linear regression analysis

The estimated marginal means of the investigated soil parameters for different fertilization treatments between 2017 and 2019 are presented in Figure 5. The effect of the different treatments on the soil parameters is clearly visible.

Based on the results of the correlation analysis (Table 6), the R_s was strongly related to DHA, and it was moderately correlated with M_{soil}, SOM, INV, and pH_{KCl}. The results revealed that INV strongly correlated with TP, and it has a moderate correlation with SOM, pH_{KCl}, BD, and DHA. There was a high positive correlation between DHA and SOM, and a very high positive correlation between DHA and pH_{KCl}. A high positive correlation was observed between SOM and pH_{KCl}. There was a very strong negative correlation between TP and BD.

According to multiple linear regression analysis, the soil respiration had a linear relationship with invertase and dehydrogenase activities (Table 7).

The accuracy of estimation (Figure 6) is $R^2 = 0.514$.

4 | DISCUSSION

Sandy soils are often characterized by poor nutrient availability with low SOM content; therefore, organic inputs are essential to enhance the quality and productivity of sandy soils (Huang & Hartemink, 2020). The soil quality highly depends on the organic matter content and the pH of the soil. SOM is a key component of the soil as it affects soil structure, nutrient availability, water retention, biodiversity, and activity (Brogniez et al., 2014; Sarker et al., 2018; Thiele-Bruhn et al., 2012). In the present study, GM treatment less affected SOM due to the rapid mineralization processes in acidic sandy soil (Weber et al., 2014) and the easily decomposable organic material of green manure (Li et al., 2019). However, the long-term incorporation of farmyard manure and SSC into the soil significantly increased the SOM content. In Westsik's long-term experiment, over a long-term period (1931–2020), the yield of rye increased in farmyard manure treatments (with or without chemical fertilizers) compared to control and green manure treatment (Hadházy et al., 2023). We consider that the increased biomass production in manure treatments could also enrich the soil with organic carbon due to the higher nutrient input. Similar results were published (Šimanský et al., 2017, 2019) that higher nutrient content through biomass production could increase SOC on sandy soil in long-term experiments. Several authors also reported the positive effect of farmyard manure and SSC compost on SOM (Hemmat et al., 2010; Oueriemmi et al., 2021), as organic manures play an essential role in humification, the formation of stable SOM fractions, and fertilization (R. Yang et al., 2016). The results of our study confirmed the claim that the long-term use of farmyard manure with chemical fertilizers increases the soil's organic carbon stock. An enhanced SOM was also observed as a result of manure application with mineral fertilizers by Sun et al. (2019). Pikuła and Rutkowska (2020) also showed that long-term (36 years) manure and mineral nitrogen fertilization combined with crop rotation improved the fertility of sandy soil. Šimanský et al. (2019) explained the increased SOM content with the stable and more resistant organic substances (including humic acids) in composted organic matter. During the composting process, bentonite also has an important role in humification, thus enhancing the degree of compost humification. Adding bentonite during composting can improve structural performance and water-holding capacity, adsorb and retain nutrients, and increase the efficiency of nutrient recycling (Lazzari et al.,

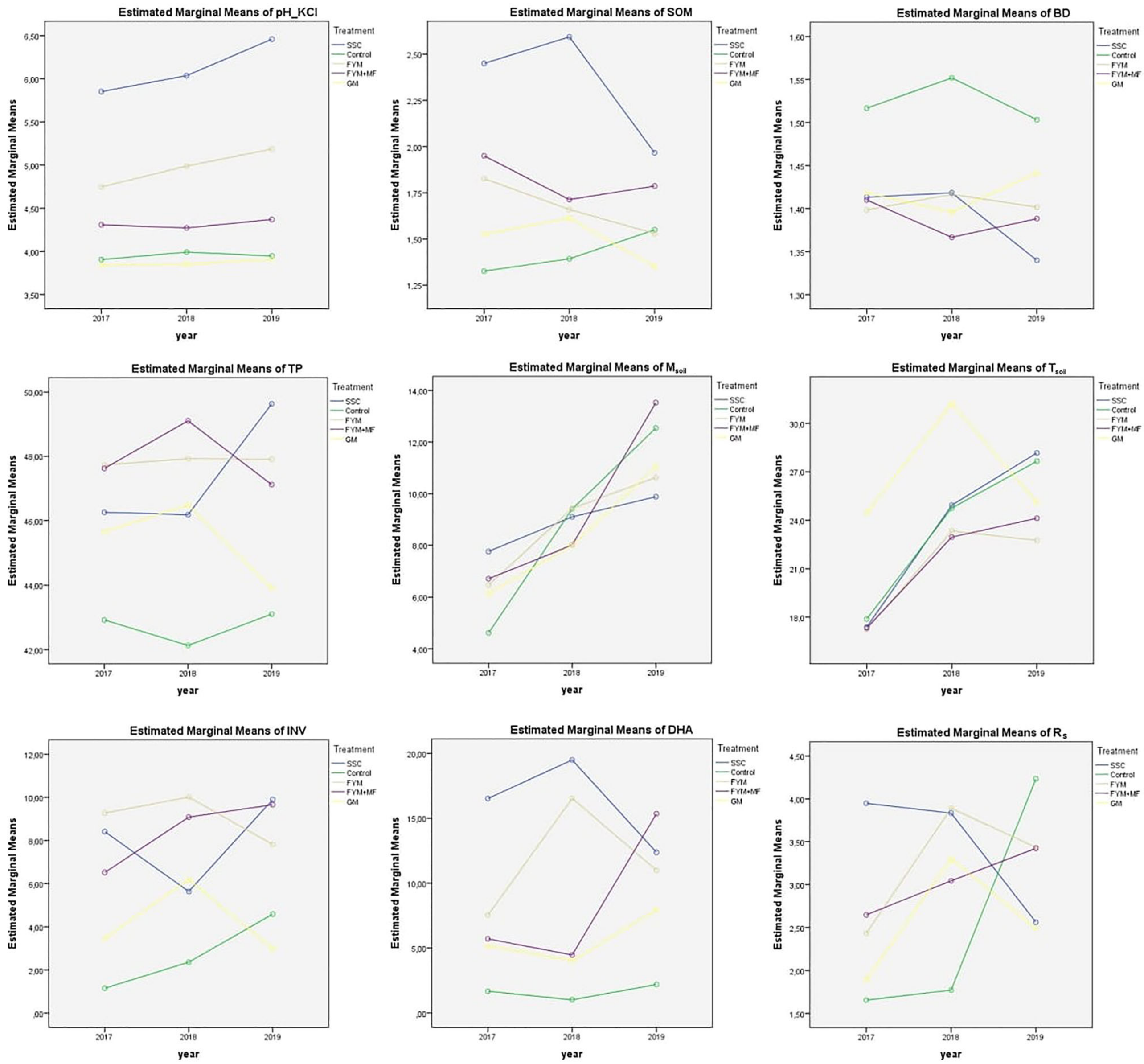

FIGURE 5 Estimated marginal means of the investigated soil parameters between 2017 and 2019. BD, bulk density; DHA, dehydrogenase activity; FYM, farmyard manure; FYM + MF, farmyard manure + mineral fertilizer; GM, green manure; INV, invertase activity; M_{soil}, soil moisture; R_s, soil respiration; SOM, soil organic matter content; SSC, Sewage sludge compost; TP, total porosity; T_{soil}, soil temperature.

2023). The increased SOM could help achieve better soil quality (W. Zhang et al., 2012) and increase organic carbon sequestration in soils (Nicolás et al., 2012). The SSC used in our experiment had a lower C/N ratio than farmyard manure. Oueriemmi et al. (2021) found SSC more balanced in terms of C and N than FYM because of the lower C/N ratio of SSC. The combined application of composted sewage sludge and farmyard manure also could be used to increase soil organic carbon and pH (Alvarenga et al., 2015).

Soil pH has a considerable effect on solubility, mobility, and adsorption, and it determines the availability of nutrients to plants in the soil solution. The pH of the soil significantly influences the soil biogeochemical processes and determines the composition of the soil microbial community (Neina, 2019). In our study, the lowest soil pH was also measured in GM treatment in addition to the control. Wang et al. (2024) also reported that the pH of loamy sand soil was unaffected by cover crop treatment. Pikuła and Rutkowska (2020) found that regular (for 36 years) application of legumes did not prevent a decrease in soil pH.

The SSC, FYM, and FYM + MF significantly increased the soil pH_{KCl} compared to control and GM. The positive effects of manure in long-term experiments, especially on soil organic carbon content and soil pH, were published in previous studies (Šimanský et al., 2017, 2019).

TABLE 6 The results of Pearson correlation analysis.

	R_s	T_{soil}	M_{soil}	SOM	pH_{KCl}	TP	BD	INV	DHA
R_s	1	0.182	0.411**	0.428**	0.510**	0.192	−0.220	0.575**	0.690**
T_{soil}	0.182	1	0.512	−0.202	−0.135	0.083	−0.227	−0.014	−0.077
M_{soil}	0.411**	0.512	1	−0.030	0.237	0.092	−0.121	0.337	0.301
SOM	0.428**	−0.202	−0.030	1	0.699**	0.123	0.015	0.441	0.670**
pH_{KCl}	0.510**	−0.135	0.237	0.699**	1	0.149	−0.132	0.532**	0.814**
TP	0.192	0.083	0.092	0.123	0.149	1	−0.911**	0.615**	0.295
BD	−0.220	−0.227	−0.121	0.015	−0.132	−0.911**	1	−0.495**	−0.312
INV	0.575**	−0.014	0.337	0.441**	0.532**	0.615**	−0.495**	1	0.547**
DHA	0.690**	−0.077	0.301	0.670**	0.814**	0.295	−0.312	0.547**	1

Note: Correlation is significant at the level $*p < 0.05$ and $**p < 0.01$.

Abbreviations: BD, bulk density; DHA, dehydrogenase activity.; INV, invertase activity; M_{soil}, soil moisture; R_s, soil respiration; SOM, soil organic matter content; TP, total porosity; T_{soil}, soil temperature.

TABLE 7 The results of multiple linear regression analysis.

		Unstandardized coefficients		Standardized coefficients		
Model		***B***	**Standard error**	***β***	***t***	**Significance**
1	(Constant)	1.659	0.141		11.794	0.000
	INV	0.078	0.024	0.257	3.211	0.002
	DHA	0.086	0.013	0.543	6.769	0.000

Note: Dependent variable: R_s.

Abbreviations: DHA, dehydrogenase activity; INV, invertase activity; R_s, soil respiration.

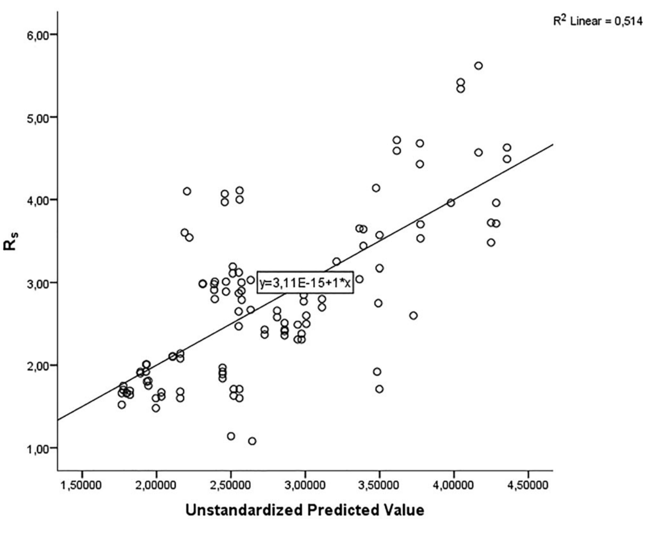

FIGURE 6 Relationship between soil respiration (R_s) and enzyme activities R_s, soil respiration.

Some reports demonstrated that compost fertilizers improved soil properties, and a significant increase could be observed in SOM and pH as a result of the addition of SSC to acidic sandy soil (Hernández et al., 2016; Silva et al., 2022; Xin et al., 2016). The organic substances could increase the pH of acidic soil through their acid/base buffering effect (Dvořáčková et al., 2022).

In general, the application of green manure can raise the amount of available nitrogen in the soil by nitrogen-fixing (R. Liu et al., 2022), which was supported by our results. Pikuła and Rutkowska (2020) also reported that regular (for 36 years) application of legumes combined with FYM increased soil nitrogen content. In our study, the SSC application significantly increased the nitrogen content of sandy soil. Yu et al. (2022) indicated that SSC application for 18 years improved soil nutrition and increased the nitrogen content of the soil as well.

The available phosphorus and potassium content of the soil significantly increased as a result of the compost and farmyard manure (with or without fertilizer) treatments. Sewage sludge compost is considered a good nutrient source and soil conditioner due to its high phosphorus content (Jakubus & Bakinowska, 2018). The application of farmyard manure could have a beneficial effect on the soil potassium availability due to its high potassium content (Kumar et al., 2021). Moreover, the combined application of SSC and farmyard manure is suggested to increase the soil nutrient supply capacity (Alvarenga et al., 2015).

The agronomic utilization of SSC has some benefits to soil. Compost application can have a favorable effect on the biological, physical, and chemical properties of the soil by increasing soil nutrients (Glab et al., 2018). In this study, the SSC application significantly increased the available Mg and Zn content of the soil, but it had no effect on the available

Cu and Mn content of the soil because of the relative low Cu and Mn content of SSC. Similar findings were published by Jakubus and Bakinowska (2018), according to which the application of SSC to the coarse-textured soil increased the HCl-extractable Cu and Zn because of its high micronutrient content.

Soil bulk density and porosity are important indicators of soil compaction, and their values strongly depend on farming systems (Xin et al., 2016). Soil bulk density influences the main soil processes and the activity of soil microorganisms as well (Meng et al., 2023). Soil porosity affects the heat, water, and airflow in soils; therefore, it has an impact on the microbial activity of soil (Fu et al., 2019).

The application of all organic fertilizers contributed to a significant decrease in the bulk density and an increase in the total porosity of sandy soil during the 3 years. Since soil organic matter is one of the most important binding agents and a significant aggregation factor, it contributes to the formation of stable soil aggregates, thereby improving the soil structure, which results in a decrease in bulk density and an increase in total porosity (Bronick & Lal, 2005; Weber et al., 2018). Schjønning et al. (1994) and Rasool et al. (2008) reported a reduction in soil bulk density on sandy soil due to the long-term application of farmyard manure. In a long-term fertilization experiment over 106 years, Naveed et al. (2014) also found a decrease in bulk density and an increase in total porosity of soil as a result of manure and NPK fertilizer amendment. Similarly, the compost application significantly affected the physical properties of sandy soil and had a positive effect on soil structure, thereby reducing soil compaction (Glab et al., 2018; Grosbellet et al., 2011; Xin et al., 2016).

Soil temperature and moisture are considered two important factors controlling SOM decomposition and thereby influencing the rate of soil respiration (D. Wang et al., 2016). During the measurements, the highest soil temperature was usually measured in GM, and the lowest was observed in FYM and FYM + MF. In the present study, the positive effects of organic treatments on soil moisture content were well expressed at lower moisture content at the first sampling time. Hernández et al. (2016) found that organic matter replenishment on sandy soil improved soil physical characteristics, promoted a good soil structure, and increased water holding capacity. The long-term organic amendment was able to reduce the temperature sensitivity of organic carbon decomposition as well (Sun et al., 2019). X. Y. Yang et al. (2011) reported that organic manure significantly increased soil water retention. Long-term application of SSC to sandy soil could increase soil water retention by adding organic and inorganic substances through improving soil structure and absorbing water molecules (Glab et al., 2018; Xin et al., 2016). These beneficial effects persisted in the soil as long as the added organic matter was protected from microbial attack through binding to clay surfaces or localization within the micropores (Singh et al., 2019).

Soil temperature and soil moisture content are known as the most crucial environmental factors affecting R_s (Fang & Moncrieff, 2001). However, in this study, only a moderate positive correlation was found between R_s and M_{soil} but not with T_{soil}. Similar findings were published by Han et al. (2017). R_s was moderately related to SOM and pH_{KCl} as well.

In 2017 and 2018, the highest rate of soil respiration was measured in SSC and FYM, and the lowest rate was detected in the control. The low soil respiration rate in control can be explained by no fertilization in control. The low CO_2 emission of soil in green manure treatment was due to the rapid mineralization of easily decomposable organic matter (Li et al., 2019). The positive changes in soil physical and chemical properties due to the application of compost and farmyard manure (with or without fertilizer) stimulated the biochemical processes and enzyme activities in the soil that resulted in increased soil respiration rate (Hernández et al., 2016; Sun et al., 2019). Kong et al. (2019) found that crop rotation management influenced the soil CO_2 respiration rate. However, in 2019, the opposite of the previous measurement results was observed. According to the previous studies, the effect of harvest on soil respiration was not consistent. The decreasing or increasing or no effect of harvest on the intensity of R_s was also reported (Čater et al., 2021; Striegl & Wickland, 1998; Olajuyigbe et al., 2012).

Soil enzyme activities are the indicators of microbial community, and they reflect changes in soil biochemical processes. Soil enzymes are important indicators of soil quality because of their early response to management and land use change (Meena & Rao, 2021). Among all enzymes in the soil environment, dehydrogenases are one of the most important and are suitable for characterizing the overall soil microbial activity (Wolińska & Stępniewska, 2012). Soil invertase plays an important role in the enzymatic degradation of soil organic carbon (Wu et al., 2023).

In the present study, the organic matter treatments provided substrates for the enzymes, which is also reflected in higher enzyme activity compared to the control (X. Liu et al., 2023). In addition, the beneficial changes in soil structure and physical and chemical parameters promoted microbial activities, especially in SSC, FYM, and FYM + MF treatments. Similar results were reported by Iovieno et al. (2009) that repeated organic amendments improved the microbial activity of soil and induced cumulative effects. Since the montmorillonite could serve as a habitat for soil microorganisms in compost due to its large specific surface area, it is also involved in the growth of soil life (Y. Zhang et al., 2020). According to Hernández et al. (2016), the beneficial effects of the composts on the microbiological soil characteristics are more noticeable in the long term with the repetitive addition of organic materials. Several authors proved that the activity of soil enzymes is influenced by different soil parameters such as soil pH, compaction, and soil organic matter content (Iovieno et al., 2009; Song et al., 2019), which is also confirmed by our results. The INV strongly correlated with TP, BD, SOM, pH_{KCl}, and there was a high positive correlation between DHA and SOM. In addition, a very high positive correlation was observed between DHA and pH_{KCl}.

5 | CONCLUSIONS

Environmentally sustainable agricultural practices are important in preserving soil quality and soil health in which soil organic matter management plays a significant role. Therefore, our purpose was to study the long-term effects of different organic amendments on the physical, chemical, and microbiological properties of acidic sandy soil.

The beneficial effect of SSC application on the parameters determining the soil quality was more pronounced compared to the impact of conventional fertilization methods. In SSC treatment, 20%–40% higher soil organic matter content and pH can be observed compared to the other organic fertilizer treatments during the study period. In addition, the long-term input of organic matter positively affected the chemical and physical properties of the soil, which resulted in more intensive soil respiration and enzyme activity, especially through the application of SSC. Based on the multiple linear regression analysis, soil respiration is related to enzyme activity and could therefore be used as a proxy for measuring enzyme activity.

This study showed that supplementing the soil with more stable and mature organic matter by compost application has a longer lasting positive effect on sandy soil compared to conventional soil improvers. The agronomic utilization of SSC offers alternative agricultural practices for improvement and nutrient supply of acidic sandy soil in an environmentally friendly way.

AUTHOR CONTRIBUTIONS

József Tibor Aranyos: Conceptualization; data curation; formal analysis; investigation; methodology; software; visualization; writing—original draft.

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CONFLICT OF INTEREST STATEMENT

The author declares no conflicts of interest.

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