DOI: 10.34101/ACTAAGRAR/1/14163

Sewage sludge compost as an alternative source of phosphorus to rye in acidic sandy soil

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SUMMARY

Today, the use of chemical fertilisers is significantly determined by their production and purchase costs, which are high. In contrast, phosphorus (P) is present in sewage sludge in a form that is easy for plants to absorb. Good quality sewage sludge compost (SSC) could contain a high quantity of P, together with other macro- and microelements and organic matter. The effect of regular SSC application on soil characteristics as well as plant parameters has been studied since 2003 in Nyíregyháza in a small plot experiment. Focusing on the P in the soil-plant system, our hypothesis was that SSC covers plants' P demand through enhancing soil P content and its plant availability in the acidic sandy soil. The effect of the SSC was examined at the doses of 0, 9, 18, and 27 t ha^{-1} on rye as a test crop. Some soil chemical parameters (pH, soil organic matter - SOM, ammonium lactate (AL) extractable P_2O_5), and the relationship between plant development (green weight, shoot length), physiological parameters (SPAD index), plant shoot P content, and soil available P content were studied. The obtained data indicated that the SOM content, pH, and available P content of the treated plots increased as a result of the long-term applied SSC compared to the control. Measurement of the relative chlorophyll content showed a strong correlation with the available P content of the soil, but surprisingly less correlation with shoot P content was found. The results of plant biomass and soil P content proved that SSC could be used as a low-cost and good source of P for plants.

Keywords: *phosphorus; soil properties; plant biomass; plant physiology; long-term experiment*

INTRODUCTION

One of the limiting factors for plant development is the available P content of the soil. The form in which the nutrients are present and how they can be mobilized is a decisive factor in plant nutrient uptake. Plants' access to nutrients depends on the form and bond the nutrients are found in the soil (Singh et al., 2022). The uptake of nutrients is influenced by several factors, including the soil physical, chemical and microbiological properties (Bennett and Klironomos, 2019; Frene et al., 2024). Most of the P forms of the soil consist of insoluble P fractions, which are not or are difficult to be absorbed by plants (Raghothama, 2005). The inorganic P is easily and directly available in the form of $H_2PO_4^-$ and HPO_4^{2-}, which are in low quantities in soil (Murphy and Sims, 2012).

The success of plant cultivation is strongly influenced by the supply of organic matter (OM) and adequate nutrients. The acidic sandy soils are poor in OM, colloids and nutrients, and have unfavorable water and heat management, the solubility and uptake of P are low (Penn and Camberato, 2019; Ogunniyi et al., 2021). The raw material of P fertilisers is not a renewable resource, the European Union has classified rock phosphate as a critical raw material (European Commission, 2017; Blackwell et al., 2019). The low-quality rock phosphate contains heavy metals such as cadmium and uranium, which are toxic to soil, plants, and humans (Bigalke et al., 2017). The inorganic phosphate content of soil quickly immobilizes with the reactive cations Ca^{2+}, Mg^{2+} of the alkaline, and Al^{3+} and Fe^{3+} of the acidic soils, resulting in water insoluble complexes (Ludewig et al., 2019).

There are many sources of organic nutrients that are not sufficiently utilised as soil amendments. Although organic fertilisers contain nutrients in a lower concentration than chemical ones and the decomposition of OM is generally slow, they have complex and positive effects on soils. The use of chemical fertilisers could lead to acidification of soil, disrupt the nutrient balance in the soil, pollute the surface and ground water, and reduce soil microbiological diversity (Francioli et al., 2016; Barros-Rodríguez et al., 2021). The increasing amount of sewage sludge associated with population growth can make it suitable for partial replacement of P fertiliser due to its high OM and increased macro- and micronutrients level, among them the available nitrogen (N), phosphorus (P), potassium (K) content. The possible way to improve the physical and chemical properties of sandy soils, to maintain healthy soil life and fertility, and to preserve biodiversity is to supply adequate OM to the soil (Roghanian et al., 2012; Sayara et al., 2020).

The above-ground biomass is determined by different factors, among them the environmental conditions (Mavromatis et al., 2002). The addition of sewage sludge with various organic substances has favorable agronomical benefits through the effect on the development parameters of plants due to valuable nutrients and a significant amount of carbon recovery (da Silva et al., 2021). For the estimation of above-ground biomass and crop yield, the chlorophyll content

DOI: 10.34101/ACTAAGRAR/1/14163

is also used in the models (Liu et al., 2019) because different chlorophyll forms play a role in the plant assimilation processes (Seaton and Walker, 1990).

In addition to replenish the soil with nutrients and OM, properly treated sewage sludge compost (SSC) improves the soil structure and water management conditions, increases crop yield, and soil biological activity (Makádi et al., 2006; Aranyos et al., 2016). Organic nutrient supplements derived from sewage sludge are among the products with a slow release of active ingredients (Talboys et al., 2016) and contain P in different forms, which type and amount depends on the wastewater treatment or the chemical composition of the composted materials (Grigatti et al., 2015). We hypothesised that long-term application of SSC could increase the soil available P content and promote the healthy development of plants. In this study, we focused on the relationship between soil P content and plant biomass, moreover, some plant physiological parameters, to determine the role of SSC in P supply of the rye plant.

MATERIALS AND METHODS

Study area and experimental design

The small plot sewage sludge compost experiment was set up in the spring of 2003 at the University of Debrecen, IAREF, Research Institute of Nyíregyháza. The study area is located at 47.988724N latitude and 21.702869E longitude and is situated at the elevation of 106 m. The typical soil type of the experimental area is Arenosol (Dystric, Lamellic Arenosol) according to WRB (2014 – updated 2015)] with 87.69% sand, 2.67% silt, 9.64% clay.

The used SSC was jointly developed by the Research Institute of Nyíregyháza and the local sewage treatment plant, Nyírségvíz Ltd. This compost is available as a product called Nyírkomposzt, and its quality meets the requirements of 36/2006. (V.18.) Decree of Ministry of Agriculture. The composition of the compost used in the experiment was: sewage sludge (40% m/m), straw (25% m/m) as organic matter, and rhyolite (30% m/m), bentonite (5% m/m) as a mineral component.

The SSC was ploughed until ~ 25 cm depth soil layer following the field application. A total of 60 plots in the experimental area were designed in 3 × 4 layouts with five replications (called as blocks in the text), in crop rotation. The size of the plots within the blocks is 12 m × 19 m. The test crops of the experiment are rye (*Secale cereale ‘Varda’*), rye with hairy vetch (*Secale cereale ‘Varda’* and *Vicia villosa ‘Hungvillosa’*), and maize (*Zea mays ‘Torino’*) from 2018. In our study the test plant was the rye. Similar to farmyard manure, the compost was applied every 3rd year after harvest at three rates so the treatments were the following: T1: 0 t ha^{-1}; T2: 9 t ha^{-1}; T3: 18 t ha^{-1}; T4: 27 t ha^{-1} SSC treatment. The control plots never received either SSC or chemical fertiliser. Apart from the SSC, the treated plots did not receive any other fertiliser. The SSC was analyzed before application in the Central Laboratory of Nyírségvíz Ltd., according to the Hungarian Standards. The pH of the applied SSC was 7.1, OM content was 24.6%, and total P_2O_5 content was 26,800 mg kg^{-1} in 2021.

Sampling and analysis

Soil and plant samples were collected during the growing season of 2023 at the end of tillering, and ear emergence stages. Composite soil samples were collected from the ploughed 0–20 cm soil layer, from each plot. Well homogenized composite samples were sieved (Ø 2 mm), air dried, and stored until the chemical measurements. Soil pH was measured in 1:2.5 soil: 1M KCl suspension (Buzás, 1988), soil organic matter (SOM) was determined according to Tyurin method (Buzás, 1988), while the plant available AL-P_2O_5 extracted according to the Hungarian Standard (MSZ 20135:1999).

Plant samples were taken from an area of 2 × 0.5 m per plot. The fresh weight of plant biomass was determined at the end of tillering and ear emergence stages. Plant P content was measured according to the Hungarian Standard (MSZ-08-1783-4:1983). The relative chlorophyll content was measured with SPAD-502 Plus chlorophyll meter (Konica Minolta, Japan). SPAD index was measured five times on the surface of a flag leave on 10 selected plants in each plot, and then the mean values of plots were used for the statistical analysis. The measurements were taken between 10:00 and 12:00 hours at the end of the ear emergence stage.

Statistical analysis

The data were evaluated with IBM SPSS v29 statistical package. The treatment effects were analyzed by one-way ANOVA while means were compared using Tukey’s HSD test at 95% significance level. The relationships among measured variables were calculated with Pearson’s correlation analysis ($p<0.05$).

RESULTS AND DISCUSSION

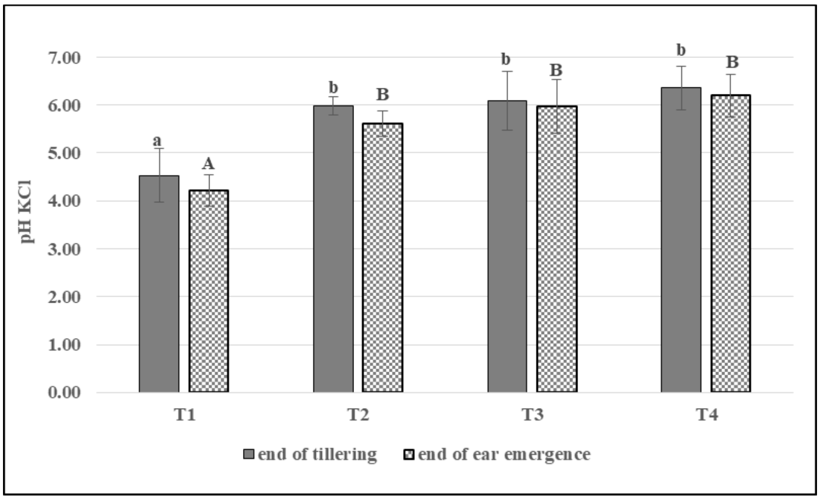
The results showed that each applied dose of the SSC significantly increased the soil pH compared to the control plots at both sampling times, mostly in the plots with doses of 18, and 27 t ha^{-1} of SSC (*Figure 1*). The pH increased from 4.5 (control) to 6.4 (27 t ha^{-1}) at the end of the tillering stage and from 4.2 (control) to 6.2 (27 t ha^{-1}) at the end of the ear emergence stage. The uptake of P and other nutrients, the soil microbial activity is influenced by soil pH (Husson, 2013). Organic substances added to the soil neutralize the effect of acids through functional groups influencing the chemical properties of humic substances (Wong and Swift, 2001). Uzinger et al. (2020) also observed the beneficial effect of compost on soil pH and OM content.

The values of the SOM were higher in all treatments compared to the control plots, especially in the 18, and 27 t ha^{-1} treatments. The values increased from 0.56% (control) to 0.78% (27 t ha^{-1}) at the end of tillering stage and from 0.67% (control) to 0.79% (27 t ha^{-1}) at the end of ear emergence stage (*Figure 2*). The last application of the SSC was two years ago, and there

DOI: 10.34101/ACTAAGRAR/1/14163

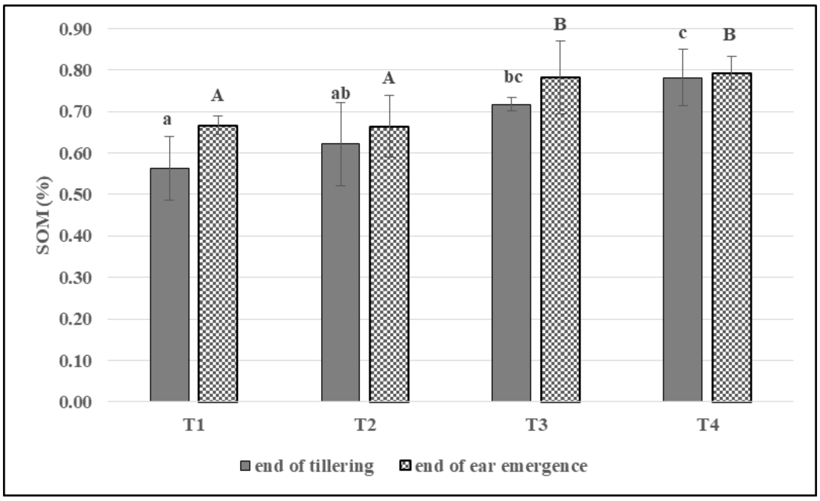
is a constant difference in the OM content between the treatments over the years. The long-term applied compost mostly keeps the OM content of soil by 18–39% higher compared to the control. The SOM is a source of macro- and microelements, it has a favorable effect on the water balance and structure of the soil. Moreover, it plays a major role in soil carbon sequestration, reduces the rapid pH changes of soil, and determines the soil microbial biomass (Zdruli et al., 2004). Based on the above mentioned changes in some soil chemical properties, the SSC application could result in favorable conditions for plant development.

Figure 1. **Soil pH (KCl) (mean±SD) in 0-20 cm layer at the end of tillering and ear emergence stages (Nyíregyháza, 2023)**



Small and capital letters indicate significant differences among treatments according to Tukey's HSD test in the two sampling times ($p<0.05$). SD: standard deviation. T1: 0 t ha^{-1}; T2: 9 t ha^{-1}; T3: 18 t ha^{-1}; T4: 27 t ha^{-1} SSC

Figure 2. **Soil organic matter (SOM) (mean±SD) in 0-20 cm layer at the end of tillering and ear emergence stages (Nyíregyháza, 2023)**



Small and capital letters indicate significant differences among treatments according to Tukey's HSD test in the two sampling times ($p<0.05$). SD: standard deviation. T1: 0 t ha^{-1}; T2: 9 t ha^{-1}; T3: 18 t ha^{-1}; T4: 27 t ha^{-1} SSC

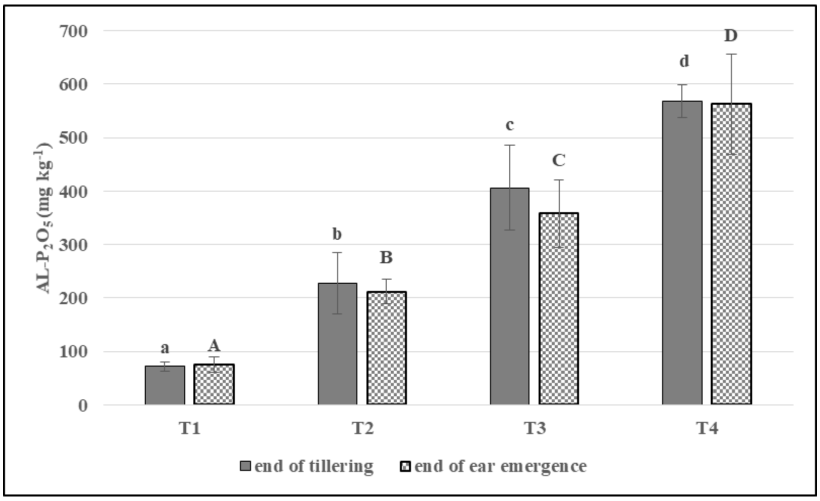
The availability of soil P is significantly influenced by soil pH through the microbial mineralization processes (Fierer and Jackson, 2006). Moreover, it is well known that soil pH below 5.5 reduces the amount of available P through the formation of complexes with Al^{3+} and Fe^{3+} (Grzebisz et al., 2024). *Figure 3* shows AL-P_2O_5 content of soil in the 0–20 cm layer. The concentration of soil AL-P_2O_5 showed a significant increase in each treatment compared to the control plots at both sampling times, where the lowest AL-P_2O_5 content was measured in the control plots (72 and 76 mg kg^{-1}, respectively), while the highest values were recorded in the 27 t ha^{-1} SSC treated plots (568 and 563 mg kg^{-1}, respectively).

The used compost contained a large amount of total P_2O_5 and it also increased the amount of solubilized P in the soil by reducing the strength of soil P adsorption onto soil particles (Bai et al., 2024). AL-P_2O_5 content slightly decreased during the flowering stage due to the more intensive P intake of plants. The amount of

DOI: 10.34101/ACTAAGRAR/1/14163

available P forms could be changed by the content of OM in the compost, through its buffering effect, or by the P access strategy of plants and soil microorganisms (Bünemann, 2015; Wang and Lambers, 2020). The SSC treatments increased the pH, thereby increasing the availability of P in the soil. The composted sewage sludge with straw increased the easily soluble fractions ($H_2PO_4^-$ and HPO_4^{2-}) of P in comparison to NPK fertiliser, farmyard manure, composted municipal waste, and composted municipal green waste (Wierzbowska et al., 2020). Results of Farsang et al. (2020) showed that composted sewage sludge delivered a larger amount of AL-P_2O_5 in 0–30 and 30–60 cm soil depth compared to the control.

Figure 3. **AL-P_2O_5 content in 0-20 cm soil layer at the end of tillering and ear emergence stages (Nyíregyháza, 2023)**

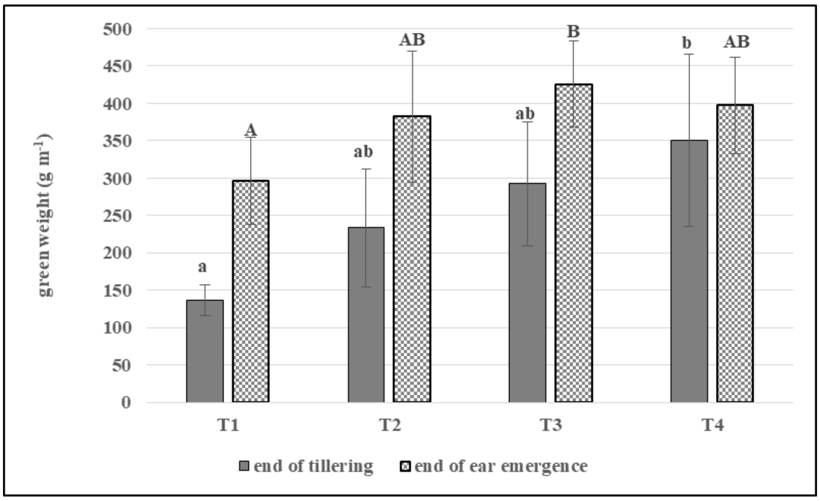


Small and capital letters indicate significant differences among treatments according to Tukey's HSD test in the two sampling times ($p<0.05$). SD: standard deviation. T1: 0 t ha^{-1}; T2: 9 t ha^{-1}; T3: 18 t ha^{-1}; T4: 27 t ha^{-1} SSC

The effect of compost treatments on plant development was represented by the green mass of the shoot at two morphological stages. All treatments caused an increase in shoot green weight (*Figure 4*), the highest mean values were obtained from the 18 and 27 t ha^{-1} SSC treatments. The higher amount of available P resulted in higher biomass by increasing the efficiency of photosynthesis.

The P participates in almost every physiological process of the plant, it builds cell-forming units like nucleic acids, phospholipids, high-energy compounds, and enzymes. In the absence of P, the development and growth of plants and roots slow down, flowering is delayed, the number of flowers, the yield, and plants' tolerance to biotic and abiotic stress decrease (Richardson et al., 2009; Jezek et al., 2023). As a result of these functions, one of the characteristics of P deficiency is the reduction of biomass.

Figure 4. **Green weight of rye at the end of tillering and ear emergence stages (Nyíregyháza, 2023)**



Small and capital letters indicate significant differences among treatments according to Tukey's HSD test in the two sampling times ($p<0.05$). SD: standard deviation. T1: 0 t ha^{-1}; T2: 9 t ha^{-1}; T3: 18 t ha^{-1}; T4: 27 t ha^{-1} SSC

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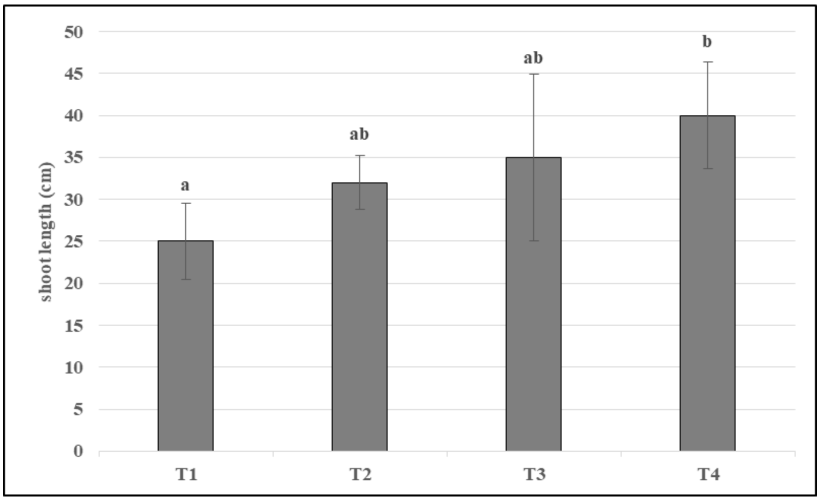
The shoot length of treated plants at the end of the tillering stage was higher compared to control plots (*Figure 5*). In the 27 t ha^{-1} SSC treatment, shoot length significantly differed from the data measured in the control treatment. In the non-treated plots, due to the limited amount of available P and other elements, plant growth was retarded. The increase in shoot mass and plant height is probably due to the fact that other nutrients, besides P, also become more available to the plants (Abd Elsalam et al., 2021).

Figure 5. **Shoot length of rye at the end of tillering stage (Nyíregyháza, 2023)**



Small letters indicate significant differences among treatments according to Tukey's HSD test ($p<0.05$). SD: standard deviation. T1: 0 t ha^{-1}; T2: 9 t ha^{-1}; T3: 18 t ha^{-1}; T4: 27 t ha^{-1} SSC

Measuring the chlorophyll content of the leaves provides information about plant assimilation processes. Plants need N and P to synthesize chlorophyll. The lack of P reduces the chlorophyll content in the photosynthesizing plant parts, as well as reduces the size and density of the stomata, which reduces the absorption of CO_2, thus reducing the efficiency of photosynthesis and the synthesis of carbohydrates (Jacob and Lawlor, 1991; Carstensen et al., 2018). The main characteristic of P deficiency is biomass reduction (Meng et al., 2021), which is illustrated well in *Figure 6*.

Figure 6. **Rye plants from control and treated plots of long-term sewage sludge compost experiment (Nyíregyháza, 2023)**

T1: 0 t ha^{-1}; T2: 9 t ha^{-1}; T3: 18 t ha^{-1}; T4: 27 t ha^{-1} SSC

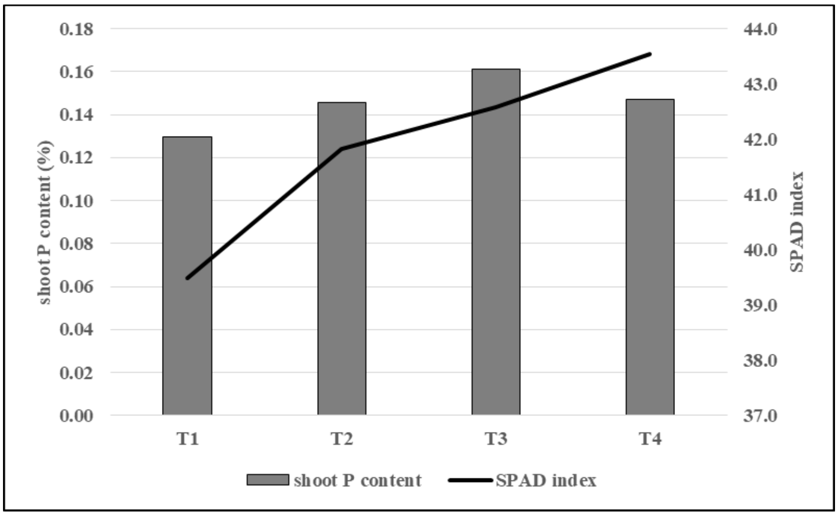
Figure 7 shows the changes in shoot P content and the SPAD index at the ear emergence stage of rye. The leaf relative chlorophyll content of treated plants is significantly higher compared to the data measured in the control plots. Our measurements indicated that the use of SSC increased photosynthetic activities and, therefore, the plant biomass production. Woźniak et al. (2024) experiments showed that the enhanced P availability might result in increased yields and improved photosynthetic activity.

The highest SPAD values were measured in the 27 t ha^{-1} doses. The applied compost doses increased the leaves relative chlorophyll contents, photosynthesis and biomass production. Several pot and field

DOI: 10.34101/ACTAAGRAR/1/14163

experiments have shown that organic fertilisers can generally enhance photosynthesis (Antolín et al., 2010; Manca et al., 2020). The SPAD index continuously increased along with the SSC doses up to 10% in the highest SSC treatment compared to the control plots (*Figure 7*). Strong correlation between SPAD index and soil AL-P_2O_5 was proved by correlation analysis (r=0.553, p=0.021) indicating the role of P in plant photosynthesis. The relationship between the plant shoot P content and AL-P_2O_5 was not significant at p<0.05 level (r=0.452, p=0.052), and the correlation between SPAD index and plant green weight was very weak (r=0.232, p=0.354).

Figure 7. **SPAD index and shoot P content at the ear emergence stage in the long-term sewage sludge compost experiment (Nyíregyháza, 2023)**



T1: 0 t ha^{-1}; T2: 9 t ha^{-1}; T3: 18 t ha^{-1}; T4: 27 t ha^{-1} SSC

CONCLUSIONS

The long-term application of sewage sludge compost on acidic sandy soil was studied in this paper. The main question was whether it could be used as a valuable phosphorus source for the test plant or not? It can be concluded that sewage sludge compost applied long-term regularly increased the level of soil organic matter and pH in compost treated plots. These are the main parameters of soils affecting the availability of elements for plants, for instance, phosphorus. Moreover, the application of sewage sludge compost on acidic sandy soil, containing a high amount of phosphorus could be a good alternative to chemical phosphorus fertilisers which was proved by the increased ammonium lactate soluble phosphorous content of the soil. Application of sewage sludge compost affected the quantity of available phosphorous content of soil not only via its high phosphorous content but also via favorable changes of soil pH, too. The enhanced availability of phosphorus resulted in increased plant biomass production and a better physiological state of the rye crop. We found that the correlation of the SPAD index with the available phosphorous content of the soil is stronger than with the plant phosphorous content. The sewage sludge compost is a complex substance increasing the level of available phosphorus which positively influenced the photosynthetic activity and plant biomass of rye. In conclusion, the beneficial effects of composted sewage sludge proved that it can be used as a low-cost and good source of phosphorus for plants.

ACKNOWLEDGEMENTS

The authors would like to say thanks to Nyírségvíz Ltd., for the continuous supply of the applied sewage sludge compost for the long-term experiment.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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