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Application of Saturation Sludge Improves Chemical Properties of Pseudogley Soil and Crop Yield

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Summary: Acidic pseudogley soils represent a significant limitation for agricultural production in Serbia due to unfavorable chemical conditions, primarily low pH and increased hydrolytic acidity, which reduce nutrient availability and crop productivity. The aim of this study was to evaluate the effect of saturation sludge, a by-product of sugar beet processing, on selected chemical properties of pseudogley soil and the yield of spring barley, soybean, and pepper. The experiment was conducted as a controlled pot experiment with four treatments: control (without sludge) and sludge application rates equivalent to 5, 15, and 25 t ha⁻¹. After one vegetation period, soil pH, hydrolytic acidity, and the availability of potassium and phosphorus were determined, together with yield parameters of the tested crops. Application of saturation sludge significantly increased soil pH and reduced hydrolytic acidity, particularly at rates of 15 and 25 t ha⁻¹. These changes were accompanied by improved availability of potassium and phosphorus and increased yield, with the most pronounced response observed in spring barley. The results indicate that saturation sludge can be recommended as an effective ameliorative material for acidic pseudogley soils; however, soil chemical analysis prior to application and further field-scale research are necessary to confirm long-term effects.

Key words: saturation sludge, pseudogley, soil, agriculture

Introduction

Soil is a natural non-renewable resource on which agricultural production takes place, and although its genesis can span over thousands of years, it can be destroyed very quickly by natural or anthropogenic degradation processes (Nachshon, 2021). Soil is distinguished by its physical, chemical, and biological properties. The chemical properties of soil include pH, organic matter content, calcium carbonate content, nutrient content, and the soil's ability to bind and accumulate nutrients. Biological properties of soil include the abundance and microbiological activity of microorganisms (Fierer et al., 2006; Delgado-Baquerizo et al., 2019). Soil fertility is closely related to soil quality. It represents soil's ability to provide satisfactory crop production with minimal use of fertilizers and manures (Diacono

& Montemurro, 2011). Threshold pH values for agricultural soils are from 3.5 to 9.5 (Rhodes, 2012). Soil pH is a major driver of soil chemical and biological processes, influencing microbial activity, nutrient availability, mineral transformations, and redox reactions in soil (Husson, 2013; Mosley et al., 2024). The availability and mobility of nutrients in soil are strongly affected by soil acidity, which significantly influences soil processes, plant development, and crop yield (Neina, 2019; Du et al., 2024). According to the data of the IUSS Working Group WRB (2015), Pseudogley soils cover 150–200 million ha of the world's surface (FAO, 2014). In the Republic of Serbia, acidic soils occupy a large part of the agricultural land of central and western Serbia, where of the total investigated area, 43% of the land has increased substitution acidity and belongs to the group of strongly acidic to acidic soils (1,197,000 ha), 20% belongs to the group of acidic to slightly acidic soils, and only 35% belongs to the group of slightly acidic to neutral soils (Ličina et al., 2011). It is well established that acidic soils are commonly associated with low availability of phosphorus and molybdenum, and often boron, whereas low pH increases the solubility and phytotoxicity of aluminum; iron toxicity may also occur, particularly in strongly acidic and waterlogged soils (Clark & Baligar, 2000; Kaiser et al., 2005; Vera-Maldonado et al., 2024; Das et al., 2017). Application of liming agents to neutralize acidity is recommended for these soil types, together with organic and mineral fertilizers, which improve soil chemical properties and production capacity (Enesi et al., 2023). Saturation sludge is used as a liming material in the reclamation of acidic soils due to its high calcium carbonate content and alkaline reaction (Ivezić et al., 2021). By neutralizing exchangeable acidity and reducing hydrolytic acidity, saturation sludge stabilizes soil pH and improves nutrient availability, particularly phosphorus and potassium, like other calcium-based liming materials (Enesi et al., 2023). In addition to its liming effect, the reuse of this industrial by-product represents an environmentally sustainable solution for waste management in the sugar industry. The pH of saturation sludge is usually around 8 or higher (Jahan Sanchary et al., 2019). Besides calcium and magnesium, it may contain smaller amounts of other elements, which can additionally influence soil fertility (Mahmud et al., 2022). Previous studies have confirmed its positive influence on soil chemical properties and crop productivity in acidic soils (Ivezić et al., 2021; Enesi et al., 2023). This study hypothesized that the application of saturation sludge improves the chemical properties of acidic pseudogley soil, particularly soil pH and hydrolytic acidity, and enhances the availability of potassium and phosphorus, thereby increasing crop yield. The objective of this study was to evaluate the effect of saturation sludge on soil pH, hydrolytic acidity, and the availability of potassium and phosphorus, as well as on the yield of spring barley, soybean, and pepper.

Materials and methods

Location and soil sampling

The soil samples were collected at the following coordinates: lat: 44.744457°, lon: 19.496384° near Šabac, from the Pseudogley soil type, from the 0-30 cm layer. The soil was characterized by low humus content, increased hydrolytic acidity, absence of CaCO₃, and acidic to slightly acidic reaction, typical for pseudogley soils. Detailed initial chemical properties are presented in Table 1. After air drying, the samples were ground and sieved through a 2 mm sieve, and used for physico-chemical analysis and mixing with the saturation sludge that is created during the process of purifying raw sugar beet juice, when the added milk of lime binds with impurities, and calcium carbonate (CaCO₃) is precipitated by saturating the juice by passing CO₂. This sediment, which adsorbs organic and mineral impurities from the juice, after filtration and dewatering, forms the final saturation sludge in the sugar factory in Crvenka. Although its detailed chemical composition was not determined within this study, previous studies report that saturation sludge typically exhibits an alkaline reaction and contains

significant amounts of calcium carbonate, which enables its use as a liming material in acidic soils (Ivezić et al., 2021; Enesi et al., 2023).

Experimental setup and treatments

This study was conducted as a controlled pot experiment under semi-controlled environmental conditions. The use of pots limits direct extrapolation of the obtained results to field conditions. The experiment was set up in four treatments with four repetitions each: control - untreated soil, treatment with 2.2 g of sludge (equivalent to 5 t ha⁻¹), treatment with 6.0 g of sludge (equivalent to 15 t ha⁻¹), treatment with 11 g of sludge (equivalent to 25 t ha⁻¹). One plant species was grown in each treatment: spring barley (*Hordeum vulgare* L.), soybean (*Glycine max* L.), and pepper (*Capsicum annuum* L.). All three crops were grown simultaneously under the same environmental conditions. For the experiment, plastic pots with a height of 15 cm and a diameter of 19 cm, with a volume of approximately 4.25 L, were used, which corresponds to a standard size suitable for growing individual plants under controlled conditions. Sixteen pots were used per treatment; each filled with 1700 g of soil. Each pot contained 10 barley plants, 5 soybean plants, or 2 pepper plants, depending on the crop species. During the experiment, the following plant characteristics were monitored: height, number of plants, flowering time, and yield. Irrigation was applied manually and empirically whenever visual observation indicated that the soil in the pots was dry in order to maintain adequate moisture conditions throughout the vegetation period.

Chemical analyses of soil

The analyses were carried out in the Laboratory for Pedology and Soil Water Regime of the Faculty of Agriculture in Novi Sad. Chemical analyses were performed on the composite sample to determine the initial state of nutrients in the soil. The results of the initial chemical analyses and applied methods are shown in Table 1.

Table 1. Results of the initial soil chemical analyses and applied methods

Parameter	Value	Unit	Method
Humus	1.87	%	Tyurin
Hydrolytic acidity	1.91	cmol kg ⁻¹	Kappen (ISO 11260:2018)
CaCO ₃	0	%	Volumetric
K ₂ O (readily available)	11.74	mg 100 g ⁻¹	AL-method
P ₂ O ₅ (readily available)	13.87	mg 100 g ⁻¹	AL-method
pH in H ₂ O	—	—	ISO 10390:2005
pH in KCl	—	—	ISO 10390:2005

Plant growing in test vessels

Phenological observations of all plant species were carried out using the BBCH scale, whereby characteristic stages of growth and development were recorded for each crop (Hack et al., 2001). Barley (*Hordeum vulgare* L.) variety Marko NS was sown on March 18th, 2019. Germination was completed on March 24th, and classified as BBCH 09. During the growing season, the phenophases of budding (BBCH 20–29), leafing (BBCH 30–39), heading (BBCH 50–59), flowering (BBCH 61–69), and ripening (BBCH 80–89) were monitored. Vegetation lasted 97 days, until June 22nd, 2019. Soybean (*Glycine max* L.) variety Renaissance (00 FAO) was sown on May 11th, 2019. Emergence is recorded as

BBCH 09, while intensive growth is characterized by stages BBCH 30–39. Flowering recorded on June 21st corresponds to the phenophase BBCH 60–69, and ripening from August 2nd until August 24th includes BBCH 80–89. Pepper (*Capsicum annuum* L.) was sown on May 11th, 2019, and germination was classified as BBCH 09. Plant growth was followed by BBCH 30–39 stages, while flowering occurred on June 22nd corresponding to BBCH 60–69. Fruit ripening, monitored until September 5th, 2019, is marked by BBCH 70–89 phenophases.

Statistical data analysis

Statistical analysis was performed using analysis of variance (ANOVA). When significant differences were detected, treatment means were compared using the Least Significant Difference (LSD) test at $p < 0.05$. Differences were considered significant at $p < 0.05$ and highly significant at $p < 0.01$. Correlation analysis was used to examine the relationships between selected soil chemical properties and yield parameters. Plant growth and canopy cover were visually assessed using the Canopeo application. The application was used exclusively for qualitative observation of canopy development and was not included in quantitative measurements or statistical analyses.

Results

Results of chemical analyses of soil in barley

The results of chemical analyses performed after the end of the vegetation period on spring barley, and statistical processing are shown in Table 2. Based on the presented chemical properties of the soil, no significant differences between the control and treatments were observed for humus content, CaCO_3 , and available phosphorus. The humus content ranged from 1.69% to 1.80% across treatments. Hydrolytic acidity showed significant differences between treatments, with higher values recorded in the control and 5 t ha⁻¹ treatment compared to 15 t ha⁻¹ and 25 t ha⁻¹ treatments. CaCO_3 was not detected in the control and in treatments 5 t ha⁻¹ and 15 t ha⁻¹, whereas a low value (0.6%) was recorded in the 25 t ha⁻¹ treatment. Soil pH in H₂O and KCl increased with increasing sludge application rates. Available potassium varied among treatments, while available phosphorus did not show statistically significant differences.

Results of statistical analyses of spring barley yield components

Results of statistical analysis of spring barley yield components are presented in Table 3. From the data shown, significant differences were observed in the mass of 1000 grains. Treatments 15 t ha⁻¹ and 25 t ha⁻¹ differed significantly from the control and 5 t ha⁻¹ treatment. No significant differences were observed between 15 t ha⁻¹ and 25 t ha⁻¹, nor between the control and 5 t ha⁻¹ treatment. Spike weight also showed significant differences, with higher values recorded at 15 t ha⁻¹ and 25 t ha⁻¹ compared to the control and 5 t ha⁻¹ treatment. Straw weight differed among treatments, with the highest value recorded at 25 t ha⁻¹. The number of grains per spike, grain weight per spike, and stem height were significantly higher in 15 t ha⁻¹ and 25 t ha⁻¹ treatments compared to the control and 5 t ha⁻¹ treatment. Yield per pot was significantly higher at 15 t ha⁻¹ and 25 t ha⁻¹ compared to the control and 5 t ha⁻¹ treatment.

In Figure 1, the results of the Canopeo application at the beginning of spring barley vegetation are shown. We can see a difference in plant coverage between the treatments. The difference between the control and the treatments is clearly visible; we see that the control marked with the letter (A) and the 5 t ha⁻¹ treatment marked with the letter (B) have the lowest plant coverage, the value of which is 6.97% for the control and 6.23% for the 5 t ha⁻¹ treatment. Compared to the control and the 5 t ha⁻¹

treatment, the 15 t ha⁻¹ treatment (C) and the 25 t ha⁻¹ treatment (D) have higher coverage, with values of 11.25% and 11.50%. In the shown Figure 2, we can see that the results of plant growth among the treatments are significant and that the plants from the treatment 25 t ha⁻¹ (D) have the highest coverage, which has a value of 17.29%, followed by the treatment 15 t ha⁻¹ (C) which has a value of 12.53%, then the treatment 5 t ha⁻¹ (B), which has a value of 11.10% and the control has the smallest recorded increase whose value is 10.43%. Figure 3 shows that the differences in the growth of spring barley plants remained until the end of the growing season, and that they have the same trend as at the beginning and middle of the growing season. We can see that the plants in the treatment 25 t ha⁻¹ (D) have the highest crop coverage of 25,19%, followed by the treatment 15 t ha⁻¹ (C) with crop coverage of 21,23%. Plants in the control (A) and 5 t ha⁻¹ (B) treatment have lower coverage with values of 12,04% and 15,08%, respectively.

Results of chemical analyses of soil in soybean

The results of soil chemical properties after soybean vegetation are shown in Table 4. Among the chemical properties, humus content, degree of hydrolytic acidity, CaCO₃ content, pH in H₂O, pH in KCl, and K₂O and P₂O₅ content are shown.

Table 2. Results of chemical analyses, after statistical analysis

Spring barley (<i>Hordeum vulgare</i> L.)							
Treatment	Humus %	Hydrolytic acidity	CaCO ₃ content	pH in H ₂ O	pH in KCl	K ₂ O content	P ₂ O ₅ content
Control	1.69 ± 0.28 A	1.77 ± 0.71 A	0.00 ± 0.00 B	7.76 ± 0.26 BC	5.80 ± 0.40 B	10.26 ± 0.23 A	11.25 ± 0.32 A
Treatment 5t ha ⁻¹	1.80 ± 0.48 A	1.87 ± 0.31 A	0.00 ± 0.00 B	7.45 ± 0.36 C	5.99 ± 0.30 B	8.04 ± 0.21 AB	11.86 ± 0.38 A
Treatment 15t ha ⁻¹	1.66 ± 0.13 A	1.12 ± 0.00 B	0.00 ± 0.00 B	8.24 ± 0.43 AB	6.63 ± 0.44 A	5.42 ± 0.24 B	14.04 ± 0.19 A
Treatment 25t ha ⁻¹	1.77 ± 0.11 A	0.56 ± 0.22 B	0.60 ± 0.27 A	8.58 ± 0.45 A	7.00 ± 0.20 A	5.42 ± 0.24 B	11.10 ± 0.25 A

*Values are presented as mean ± SD (n = 4). Statistical differences among treatments were determined by one-way ANOVA followed by the LSD test at p < 0.05. Different letters within a row indicate significant differences between treatments.

Table 3. Results of statistical analysis of spring barley yield components

Spring barley (<i>Hordeum vulgare</i> L.)							
Treatment	Mass of 1000 grains (g)	Spike weight (g)	Straw weight (g)	Number of grains per spike	Grain weight per spike (g)	Stem height (cm)	Yield per pot (g)
Control	552.5 ± 93.02 B	0.7 ± 0.12 B	0.3 ± 0.04 C	12 ± 1.94 B	0.5 ± 0.09 B	44.0 ± 2.75 B	5.5 ± 0.93 B
Treatment 5t ha ⁻¹	595.7 ± 139.99 B	0.7 ± 0.15 B	0.4 ± 0.08 B	12 ± 3.07 B	0.6 ± 0.14 B	44.0 ± 3.72 B	5.9 ± 1.43 B
Treatment 15t ha ⁻¹	873.7 ± 91.48 A	1.0 ± 0.11 A	0.6 ± 0.10 AB	17 ± 2.49 A	0.9 ± 0.09 A	51.0 ± 3.72 A	8.7 ± 0.91 A
Treatment 25t ha ⁻¹	900.2 ± 59.31 A	1.1 ± 0.07 A	0.6 ± 0.10 A	17 ± 1.41 A	0.9 ± 0.06 A	44.0 ± 1.19 B	9.1 ± 0.59 A

*Values are presented as mean ± SD (n = 4). Statistical differences among treatments were determined by one-way ANOVA followed by the LSD test at p < 0.05. Different letters within a row indicate significant differences between treatments.

Presentation of the results of coverage and lushness of spring barley with the Canopeo application at the beginning, middle, and end of the growing season

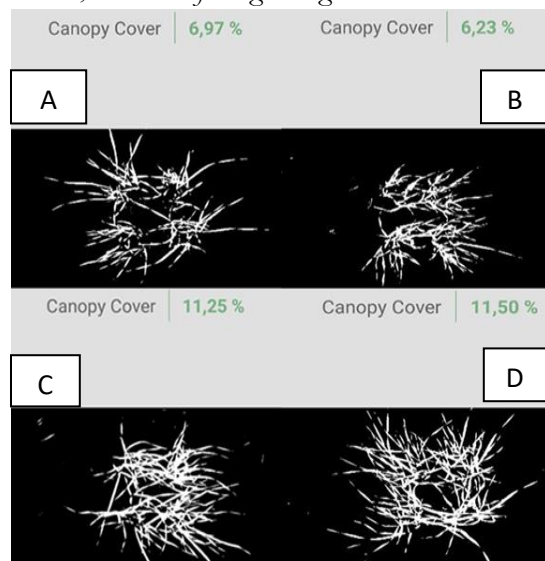


Figure 1. The beginning of spring barley vegetation

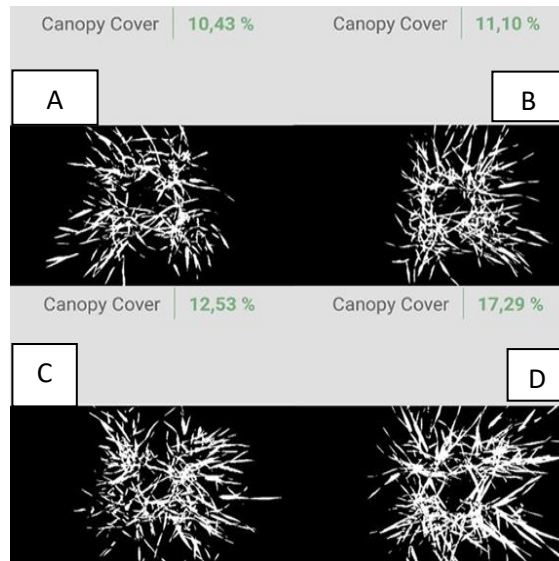


Figure 2. Middle of spring barley vegetation

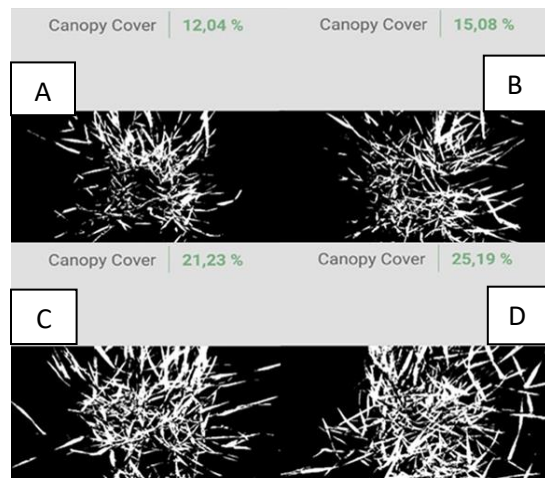


Figure 3. The end of spring barley vegetation

The results of soil chemical analyses after soybean cultivation are presented in Table 4. No significant differences were observed in humus content and available phosphorus between treatments and the control. Hydrolytic acidity showed significant differences, with higher values recorded in the control compared to the sludge treatments. CaCO_3 was not detected in the control and in treatments 5 t ha^{-1} and 15 t ha^{-1} , while a low value (0.62%) was recorded in the 25 t ha^{-1} treatment. Soil pH in H_2O and KCl increased with increasing sludge application rates. Available potassium was classified as low in all treatments.

Table 4. Soil chemical properties analysed during the vegetation period of soybean

Soybean (<i>Glycine max</i> L.)							
Treatment	Humus %	Hydrolytic acidity	CaCO ₃ content	pH in H ₂ O	pH in KCl	K ₂ O content	P ₂ O ₅ content
Control	1.92 ± 0.08 A	2.06 ± 0.48 A	0.00 ± 0.00 B	7.50 ± 0.45 C	6.30 ± 0.07 B	5.83 ± 0.18 A	14.66 ± 0.29 A
Treatment 5t ha ⁻¹	1.95 ± 0.10 A	0.84 ± 0.19 B	0.00 ± 0.00 B	7.89 ± 0.19 BC	6.70 ± 0.23 A	4.81 ± 0.24 A	14.80 ± 0.23 A
Treatment 15t ha ⁻¹	1.72 ± 0.06 B	1.03 ± 0.36 B	0.00 ± 0.00 B	8.34 ± 0.31 AB	7.29 ± 0.23 C	8.04 ± 0.27 A	19.77 ± 0.28 A
Treatment 25t ha ⁻¹	1.62 ± 0.05 B	0.93 ± 0.38 B	0.62 ± 0.28 A	8.45 ± 0.05 A	7.45 ± 0.20 C	5.62 ± 0.26 A	15.83 ± 0.29 A

*Values are presented as mean ± SD (n = 4). Statistical differences among treatments were determined by one-way ANOVA followed by the LSD test at p < 0.05. Different letters within a row indicate significant differences between treatments.

Results of statistical analysis of soybean yield components

Statistical analyses of soybean yield components from the sample part of this study are shown in Table 5. Significant differences were observed in the mass of 1000 grains, where treatments 15 t ha⁻¹ and 25 t ha⁻¹ showed higher values compared to the control and 5 t ha⁻¹ treatment. No significant differences were observed in the number of pods per plant, pod weight, grain weight per plant, or stem weight. The number of grains per pod differed among treatments, with the highest value recorded at 25 t ha⁻¹. Stem height was significantly higher at 15 t ha⁻¹ compared to other treatments. No statistically significant differences were observed in yield per pot between treatments and the control. Presentation of the results of coverage and lushness of soybean with the Canopeo application at the beginning, middle, and end of the growing season.

Table 5. Results of statistical analysis of soybean yield components

Soybean (<i>Glycine max</i> L.)								
Treatment	Mass of 1000 grains (g)	Number of pods per plant	Number of grains per pod	Weight of pods per plant (g)	Weight of grains per plant (g)	Stem weight (g)	Stem height (cm)	Yield per pot (g)
Control	1079.8 ± 76.73 B	4.2 ± 0.6 A	2.1 ± 0.12 C	2.3 ± 0.20 A	1.3 ± 0.41 A	1.4 ± 0.14 A	43.8 ± 2.03 B	6.7 ± 0.68 A
Treatment 5t ha ⁻¹	1058.1 ± 105.52 B	3.9 ± 0.75 A	2.2 ± 0.28 BC	2.3 ± 0.82 A	1.5 ± 0.62 A	1.0 ± 0.62 A	44.3 ± 4.28 B	7.5 ± 3.09 A
Treatment 15t ha ⁻¹	1386.5 ± 173.01 A	3.6 ± 0.53 A	2.4 ± 0.10 AB	2.2 ± 0.22 A	1.4 ± 0.68 A	1.1 ± 0.17 A	51.1 ± 2.32 A	6.9 ± 0.87 A
Treatment 25t ha ⁻¹	1465.5 ± 212.36 A	4.2 ± 0.26 A	2.5 ± 0.12 A	2.2 ± 0.21 A	1.5 ± 0.23 A	1.3 ± 0.21 A	43.8 ± 1.61 B	7.1 ± 1.06 A

* Values are presented as mean ± SD (n = 4). Statistical differences among treatments were determined by one-way ANOVA followed by the LSD test at p < 0.05. Different letters within a row indicate significant differences between treatments.

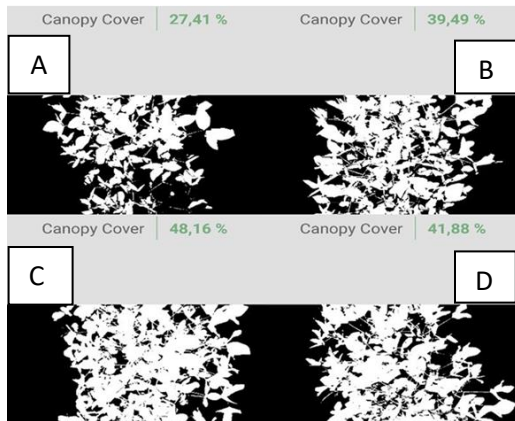


Figure 4. The beginning of soybean vegetation

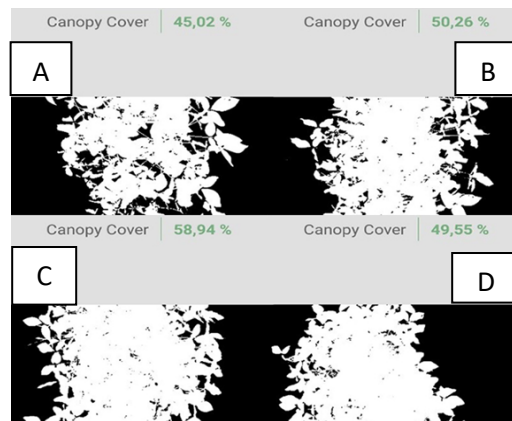


Figure 5. Middle of soybean vegetation

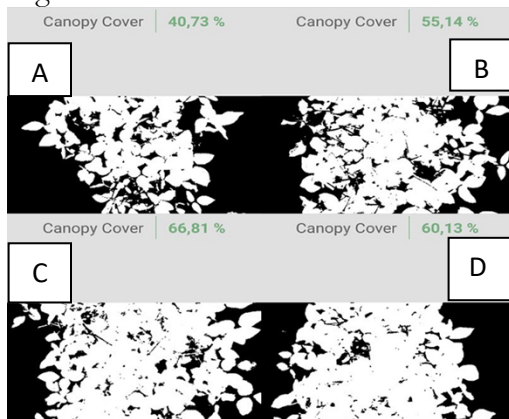


Figure 6. The end of soybean vegetation

In Figure 4, we see the digital display, and the differences in the growth and coverage of plants at the beginning of the soybean vegetation period among the treatments, where we can see that the plants in the treatment 15 t ha^{-1} (C) with a value of 48.16% have the highest growth, followed by the plants in the treatment 25 t ha^{-1} (D) with a value of 41.88%, and then the plants in the treatment 5 t ha^{-1} (B) with a value of 39.49%, while the control plants (A) have the lowest coverage with 27.41%. From the results shown in Figure 5, we can see that during the growing season there were changes in the growth of plants among the treatments, and that the plants in the treatment 15 t ha^{-1} (C) have the highest growth with a coverage of 58.94%, followed by the plants in the treatment 5 t ha^{-1} (B) with coverage of 50,26% then the plants in the treatment 25 t ha^{-1} (D) with a value of 49,55%, and that the plants in the control (A) have the lowest coverage with a value of 45.02%. The results shown in Figure 6 display no significant changes in plant coverage, and the growth trend remained the same as in the previous period in all treatments.

Results of chemical analyses of the soil in pepper

The results for soil chemical properties in pepper are shown in Table 6. The chemical properties include humus content, degree of hydrolytic acidity, CaCO_3 content, pH in H_2O , pH in KCl, and K_2O and P_2O_5 content. No significant differences were observed in humus content between treatments and the control. Hydrolytic acidity differs between treatments and the control. It is observed that the degree of hydrolytic acidity is higher in the control and treatment 5 t ha^{-1} (A)

compared to the treatments 15 t ha⁻¹ and 25 t ha⁻¹ (B). The CaCO₃ content was not observed in the control and treatments 5 t ha⁻¹ and 15 t ha⁻¹ (B), whilst only 0.70% was found in the treatment 25 t ha⁻¹. Soil pH in both H₂O and KCl, as well as K₂O and P₂O₅ content, differ between treatments and the control.

Table 6. Chemical properties of the soil, obtained after the pepper vegetation period

Pepper (<i>Capsicum annuum</i> L.)							
Treatment	Humus %	Hydrolytic acidity	CaCO ₃ content	pH in H ₂ O	pH in KCl	K ₂ O content	P ₂ O ₅ content
Control	1.86 ± 0.15 A	1.96 ± 0.19 A	0.00 ± 0.00 B	7.66 ± 0.36 A	5.29 ± 0.42 B	13.69 ± 0.26 A	15.80 ± 0.26 B
Treatment 5t ha ⁻¹	1.69 ± 0.16 A	2.15 ± 0.47 A	0.00 ± 0.00 B	7.02 ± 0.51 B	5.98 ± 0.29 C	12.08 ± 0.23 AB	11.08 ± 0.26 A
Treatment 15t ha ⁻¹	1.83 ± 0.13 A	0.93 ± 0.21 B	0.00 ± 0.00 B	6.92 ± 0.18 B	6.35 ± 0.23 C	11.47 ± 0.26 AB	13.56 ± 0.33 AB
Treatment 25t ha ⁻¹	1.66 ± 0.12 A	0.56 ± 0.22 B	0.70 ± 0.13 A	8.12 ± 0.30 A	6.94 ± 0.52 A	10.26 ± 0.24 B	14.45 ± 0.27 B

* Values are presented as mean ± SD (n = 4). Statistical differences among treatments were determined by one-way ANOVA followed by the LSD test at p < 0.05. Different letters within a row indicate significant differences between treatments.

Results of statistical analysis of pepper yield components

After collecting data on yield components, statistical analyses were performed, and their results are shown in Table 7. No significant differences were observed between treatments and the control for fruit length, fruit width, and fruit weight. Significant differences were recorded in stem height, with the highest value observed in the control and the lowest value in the 25 t ha⁻¹ treatment. Yield per pot differed significantly among treatments. The highest yield was recorded at 15 t ha⁻¹, while the lowest was observed at 5 t ha⁻¹. The control and 25 t ha⁻¹ treatment did not differ significantly from each other.

Table 7. Results of statistical analysis of pepper yield components

Pepper (<i>Capsicum annuum</i> L.)					
Treatment	Fruit length (cm)	Fruit width (cm)	Fruit weight (g)	Stem height (cm)	Yield per pot (g)
Control	4.8 ± 0.70 A	4.7 ± 0.28 A	41.9 ± 3.14 A	33.2 ± 2.18 A	93.5 ± 15.67 AB
Treatment 5 t ha ⁻¹	4.2 ± 3.08 A	3.3 ± 2.28 A	27.8 ± 21.80 A	31.8 ± 6.52 AB	55.7 ± 43.61 C
Treatment 15 t ha ⁻¹	5.6 ± 0.61A	4.4 ± 0.51 A	39.1 ± 13.45 A	28.1 ± 1.38 AB	112.5 ± 14.97 A
Treatment 25 t ha ⁻¹	5.4 ± 0.60 A	3.8 ± 0.62 A	31.0 ± 7.45 A	27.6 ± 1.11 B	86.2 ± 15.39 AB

*Values are presented as mean ± SD (n = 4). Statistical differences among treatments were determined by one-way ANOVA followed by the LSD test at p < 0.05. Different letters within a row indicate significant differences between treatments.



Figure 7. The beginning of pepper vegetation



Figure 8. The middle of pepper vegetation

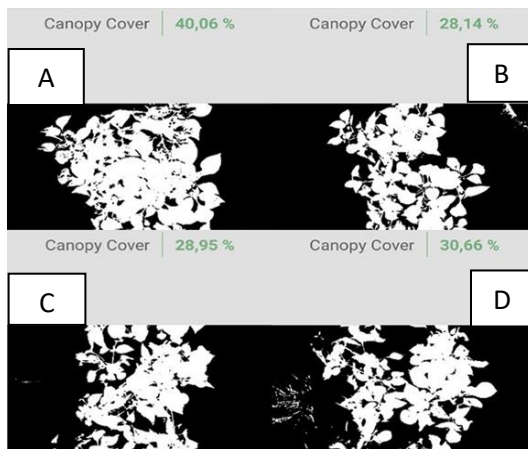


Figure 9. The end of pepper vegetation

In Figure 7, we can see that the plants in the 25 t ha⁻¹ treatment (D) have the highest coverage of 21,91%, while those in the 15 t ha⁻¹ treatment (C) have slightly lower coverage (20,82%). As expected, the control (A) and the 5 t ha⁻¹ treatment (B) have the lowest plant coverage, 14,29% and 16,04% respectively. In Figure 8, we can see minor changes in plant growth. We see that the plants in the control (A) have a higher growth value of 21,63% than the plants in the 5 t ha⁻¹ treatment (B), whose value is 20,37%, and that the plants in the 25 t ha⁻¹ treatment (D) still have the highest coverage (27,89%). In Figure 9, the results for the end of the vegetation period show that there were significant changes in the growth of plants and chlorophyll synthesis, especially in the control treatment (A), which can be described by the lesser development of the plants at the beginning of the vegetation season, due to unfavorable weather conditions. The other treatments maintained the tendencies they had throughout the entire vegetation period.

Discussion

The observed increase in soil pH and reduction of hydrolytic acidity across all treatments and crop variants confirm the liming effect of calcium carbonate present in saturation sludge. Similar relationships between soil pH and hydrolytic acidity have been reported in long-term studies examining the impact of liming materials on acidic soils (Pepo, 2021). The effectiveness of CaCO₃-based amendments in regulating soil acidity has been widely documented (Lato et al., 2025; Goulding,

2016). The stabilization of soil reaction toward neutral values observed in higher sludge treatments indicates improved chemical conditions in acidic pseudogley soil. Although phosphorus availability did not significantly differ among treatments, stabilization of pH may enhance nutrient dynamics and uptake efficiency over time. Previous research suggests that liming and the combined application of organic and mineral fertilizers influence potassium and phosphorus availability in acidic soils (McBride, 1994; Chen et al., 2023). Spring barley showed the most pronounced response to sludge application. Significant improvements in grain mass and yield per pot at higher application rates are consistent with previous findings that highlight the beneficial effects of liming and calcium addition on cereal productivity in acidic soils (Živanović et al., 2000; Katić et al., 2006; Mandić et al., 2016; Singbah et al., 2025; Kumar et al., 2023; Chen et al., 2023). These results confirm the importance of soil amelioration measures for improving barley productivity under acidic conditions. Soybean exhibited a more moderate response. Although total yield per pot did not differ significantly among treatments, significant differences were observed in certain yield components, particularly the mass of 1000 grains and the number of grains per pod. This suggests that the reduction of soil acidity contributed to partial improvement in yield formation. However, the absence of significant differences in total yield may also reflect environmental factors during the growing period, which include lower air temperatures in early developmental stages. Previous studies have reported yield increases of 10–40% following liming and combined fertilizer application in acidic soils (Kumar et al., 2023; Singbah et al., 2025), supporting the assumption that soybean response depends on both soil chemical improvements and environmental conditions. Pepper response differed from that of barley and soybean. Although fruit morphological traits did not significantly differ among treatments, variations in yield per pot indicate a positive response to moderate sludge application rates, particularly at 15 t ha⁻¹. Improved soil pH and reduced hydrolytic acidity may have contributed to more favorable nutrient availability and root development. Similar effects of liming and calcium-containing amendments on vegetable crop productivity in acidic soils have been reported by Kumar et al. (2023), and Chen et al. (2023). Nevertheless, the variability among treatments suggests that pepper's response to soil amelioration is influenced not only by chemical improvements but also by crop-specific physiological characteristics and environmental conditions. Overall, the findings indicate that saturation sludge application improves soil chemical properties of acidic pseudogley soil and can positively affect crop productivity, particularly in cereal crops. However, crop response varies among species and depends on environmental factors, emphasizing the need for further field-scale research to evaluate long-term agronomic and environmental effects.

Conclusion

The results obtained during one vegetation period under pot experimental conditions demonstrate that the application of saturation sludge improved key chemical properties of acidic pseudogley soil. The most significant effects were observed in the reduction of hydrolytic acidity and stabilization of soil pH at higher application rates (15 t ha⁻¹ and 25 t ha⁻¹). Improved soil chemical conditions were reflected in enhanced plant growth and yield, particularly in spring barley, while soybean and pepper exhibited moderate responses depending on the yield component analyzed. These findings indicate that saturation sludge can serve as an effective ameliorative material for acidic pseudogley soils. However, prior soil chemical analysis is necessary to determine hydrolytic acidity levels and define the appropriate application rate in order to avoid plant stress caused by rapid changes in soil reaction. Additionally, chemical characterization of the sludge itself is recommended before application. Further field-scale studies are required to confirm the long-term agronomic and environmental effects of this ameliorative practice.

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Primena saturacionog mulja i efekti na hemijske osobine pseudoglejnog zemljišta i prinos biljaka

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Sažetak: Veliki deo obradivih površina u Republici Srbiji čine zemljišta kisele reakcije. Oko 43% obradivih površina zapadne, centralne Srbije i Šumadije obuhvataju kisela zemljišta sa nepovoljnim fizičko-hemijskim osobinama, na kojima je poljoprivredna proizvodnja otežana bez primene meliorativnih mera. U zapadnoj i centralnoj Srbiji oko 250.000 ha čine zemljišta tipa pseudoglej, koja se odlikuju dugotrajnim zadržavanjem površinskih voda, nepovoljnim oksido-redukcionim procesima i visokim stepenom hidrolitičke kiselosti. Saturacioni mulj, nusproizvod prerade šećerne repe, pokazao se kao efikasno meliorativno sredstvo za smanjenje kiselosti i poboljšanje hemijskih osobina zemljišta. Eksperimentalni rad sa različitim količinama mulja pokazao je da biljke pozitivno reaguju na smanjenje hidrolitičke kiselosti, što se ogleda u većem porastu i prinosu biljaka pri višim dozama. Najbolji rezultati postignuti su pri primeni 15 t ha⁻¹ i 25 t ha⁻¹ saturacionog mulja, gde su biljke imale veću nadzemnu masu, prinos i pokrovnost u odnosu na kontrolu i tretman od 5 t ha⁻¹. Zemljište tretirano višim dozama mulja imalo je niži stepen hidrolitičke kiselosti i veći sadržaj lako pristupačnih oblika fosfora i kalijuma. Pravilna i pravovremena primena meliorativnih sredstava, u kombinaciji sa organskim đubrivima, doprinosi poboljšanju fizičko-hemijskih osobina zemljišta, povećanju prinosa i dugoročnoj ekonomskoj stabilnosti poljoprivrednih proizvođača.

Ključne reči: poljoprivreda, pseudoglej, saturacioni mulj, zemljište