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Article

Effect of Various Rates of P from Alternative and Traditional Sources on Butterhead Lettuce (*Lactuca sativa* L.) Grown on Peat Substrate

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Abstract: Previous research indicated the potential use of struvite (STR) as an alternative source of phosphorus (P) in crop production. A greenhouse experiment was conducted to evaluate the effect of STR and triple superphosphate (TSP) on the growth and chemical composition of butterhead lettuce grown on peat substrate over a three-month period (May–July). Both alternative (STR) and conventional (TSP) fertilizers were applied at three rates: (1) recommended rate based on the elemental content of substrate and crop nutritional need; (2) reduced rate (50% lower than recommended); and (3) increased rate (50% higher than recommended). Unfertilized (control) plants were also grown in the pot experiment. As expected, fertilizer application tended to increase the content of heavy metals in the substrate. Thus, an increase in Zn, Pb, and Cu content in peat substrate was found following STR amendments. However, compared with unfertilized plants, the applied rates of the STR and TSP fertilizers did not increase the content of Cd and Cu in the plant leaf, while Hg content was below the detection limit. In addition, Zn content in the plant leaf significantly decreased following STR and TSP applications. In comparison to unfertilized plants, both alternative and conventional fertilizers increased the content of P and nitrate nitrogen ($N\text{-}NO_3^-$) in the plant leaf while their effect on Mg content was negligible. The increased rate of STR was the best fertilizer treatment because it produced the largest number of leaves, which were also characterized by the highest P content. Our findings showed that STR was an effective source of P in butterhead lettuce cultivation without adverse effects on heavy metal accumulation.

Keywords: peat; sewage sludge; struvite; superphosphate; P uptake; P content; Mg content; Mg uptake; heavy metals

1. Introduction

Phosphorus is a basic element that is essential in many important biological processes in all forms of life [1,2]. This element is a structural component of all living organisms as a component of nucleic acids, and, together with nitrogen (N) and potassium (K), represents one of the main nutrients for plants. It is responsible for vital functions related to the growth and development of plant cellular processes. Phosphorus influences seed germination, seedling establishment, root, shoot, flower and seed development as well as photosynthesis, respiration and nitrogen fixation processes [1–3]. Its functions include energy transfer, transformation of sugars and starches, nutrient movement within the plant and the transfer of genetic code characteristics from one generation to the next [4]. Its availability in soil is rarely sufficient for optimum growth and development of plants. However, its excess (just as with N) leads to a deterioration in the quality of surface waters by eutrophication [5,6].

Phosphorus is taken up by plants in the form of the anion $H_2PO_4^-$ and HPO_4^{2-}. Its availability is closely related to soil reaction and temperature (below 10 °C a limited uptake is observed). Its uptake is favourable in the pH range 5.0–6.0, where it predominates in the monovalent form ($H_2PO_4^-$) [3]. The optimum supply of P to plants intensifies the growth of the root system and thus leads to a better utilization of nutrients from soil or substrate [3]. Traditional P fertilizers come from rock phosphate, which nowadays is a limited resource and will be depleted within the next 150–250 years [7,8] and thus P is subject to special attention [9]. Recovery of P is limited to the agriculture sector because this sector is mostly based on P and materials rich in this element can be found [10–12]. Therefore, as a result, there is growing interest in the efficient recovery of nutrients from waste.

Presently, we distinguish technology for P recovery based on precipitation from sewage sludge that can be precipitated in the form of STR, hydroxyapatite or calcium phosphate [9,13,14]. The main advantage of this technology is the possibility to receive P fertilizer with high quality that can be used directly in agriculture [12]. An interesting source of P supply for farms is STR (magnesium ammonium phosphate) [15]. It is an alternative P fertilizer with valuable properties containing macro elements needed by plants [10,16,17]. This fertilizer is still not implemented as a mineral fertilizer under general EU regulations, but these are currently being revised to recommend the allowance of STR into the EU fertilizer market [18,19]. Struvite is comparable to other P fertilizers because it provides nutrients such as Mg and N, and has additional environmental benefits such as helping to reduce phosphate rock consumption and reducing P release through the discharge of treated effluent into surface and groundwater resources [11,15,18,20]. Because of its low solubility, it is not washed to ground water or inside the soil, which would limit its availability for plants. The fertilizer elements are released slowly, which reduces the need for frequent fertilization [21]. Magnesium ammonium phosphate (MAP) is used to fertilize grass, tree seedlings, ornamental plants, vegetables, flowers and lawn gardens [22]. Struvite represents a longer lasting source of P for crop growth than easily soluble forms of P, while preventing P sorption onto soil components or loss through leaching or runoff [23]. From 59 available publications, most experiments (307 STR observations) with plant responses were mainly conducted on the greenhouse scale (78%) and to a lesser extent on the field scale (22%) [18].

The conducted experiments present a comparable or better efficiency of STR compared to other P fertilizers both in field and pot studies. Higher values under STR fertilization were demonstrated in lettuce cultivation [20], cabbage cultivation [24], Sudan grass [25] or grasses, corn, vegetables, and fruits [26] compared to traditional fertilizers. Additionally, Mg content in STR means that this form is more effective compared to other fertilizers. Fertilization with STR also leads to increased P content and uptake by plants, while not causing contamination of plants by heavy metals [6]. Plants fertilized with STR may have lower concentrations of heavy metals compared to conventional fertilizers [6].

The use of organic-mineral fertilizers is becoming increasingly common in agriculture. These fertilizers that are produced on the basis of P recovery fall completely within the scope of the closed loop economy linked to wastewater treatment plants, where the primary material is used to recover P and the final step, the most important for the farmer, is to obtain a valuable and safe fertilizer. In order for such fertilizer to be accepted by the farmer, it must be tested.

On the other hand, next to sewage sludge, fertilizers based on sewage sludge production or other organic wastes [27], such as meat and bone meals, can be a viable alternative to P fertilizers [28]. Meat and bone meal is a by-product of the rendering industry and is regarded an excellent potential organic fertilizer because of balanced nutrient availability [28,29]. Animal meals, especially meat and bone meal are a rich source of N and P for crops [30] as a slow-release fertilizer, as a comparable feature to Phosgreen [28,29]. They have a beneficial effect on plants with a long period of growth and this effect is noticeable in the years following application [31,32]. Most importantly, the nutrients in those fertilizers are in biological form [32]. Nitrogen supplied to crops in the form of this fertilizer is available already in the first year and is able to cover 80% of the fertilizer needs of cereals for this element [33].

We hypothesized that STR fertilization caused an increase in P and Mg content in both the plant material and peat leading to higher uptake of these elements by butterhead lettuce. Although a significant number of studies have been conducted to investigate the agronomic value of STR, there is limited information on the efficacy of the role of STR on peat properties and the impact of nitrate nitrogen ($N\text{-}NO_3^-$) content. The objective of this study was to evaluate the potential use of commercial STR fertilizer (Phosgreen) as an alternative source of P, compared to traditional P fertilizer (TSP) for the cultivation of the test plant (butterhead lettuce) grown on deacidified peat substrate.

2. Materials and Methods

2.1. Experiment Setup and Establishment

This work was conducted at the Research and Education Station in Psary, belonging to the Department of Horticulture at Wroclaw University of Environmental and Life Sciences. Two P fertilizers were used in the experiment: a traditional commercial one (TSP) commonly used in butterhead lettuce cultivation and an ecological one based on sewage sludge production. The fertilizers were assessed for heavy metal content. A pot experiment under greenhouse conditions was conducted in two series during May–July 2021. In the experiment, the effect of Phosgreen was examined compared to a TSP commercial fertilizer. The TSP used in the study was bought from Ampol Merol (Wąbrzeźno, Poland) as an enriched fertilizer with lime containing 40% mineral phosphate and was 10% CaO soluble in water and recommended as a standard P fertilizer for application on crops. A sludge-based fertilizer, STR, from Krevox (Piaseczno, Poland) was characterized with the following composition: 2% N, 28% P, 12% Mg, 0% K, pH 9.2 and low heavy metal content compared to TSP (Table 1).

Table 1. Selected heavy metal contents in TSP and STR fertilizers. Results given as a mean ±standard deviation (database of own study).

P Fertilizer	Heavy Metal Content (mg kg^{-1})			
	Zn	Pb	Cu	Cd
TSP	213 ± 43	1.8 ± 0.4	23 ± 4.8	10.7 ± 2.1
STR	3.7 ± 0.7	<0.1	1.7 ± 0.3	<0.1

Ready, packed, deacidified peat was used in the greenhouse experiment. This horticulture media was thoroughly mixed with fertilizers and the pH was checked with a portable pH meter before use. The chemical composition of the peat was as follows: pH in the water 5.6; salinity 1.4 g NaCl dm^{-3}, available N 230 mg dm^{-3}, P 180 mg dm^{-3}, K 230 mg dm^{-3} and Mg 150 mg dm^{-3}.

The deacidified peat substrate was characterized by a standard nutrient concentration which was modified by adding mineral fertilizer for appropriate plant nutrient demand. Before the start of experiment, ammonium nitrate (AN) at 122.4 mg L^{-1} and potassium sulfate (PS) at 300.0 mg L^{-1} were mixed with peat substrate. Both alternative (STR) and conventional (TSP) fertilizers were applied at three rates: (1) recommended rate based on the elemental content of substrate and crop nutritional need; (2) reduced rate (50% lower than recommended); and (3) increased rate (50% higher than recommended).

Rates of alternative (STR) and conventional (TSP) fertilizers were as follows:

TSP reduced rate—17 mg L^{-1}
STR reduced rate—29 mg L^{-1}
TSP recommended rate—34 mg L^{-1}
STR recommended rate—57 mg L^{-1}
TSP increased rate—68 mg L^{-1}
STR increased rate—114 mg L^{-1}

Unfertilized (control) plants were also grown in the pot experiment. Butterhead lettuce seedlings were received to be quilted. At the stage of 4 developed leaves, the seedling was quilted into 12 dm^3 boxes. Four seedlings were planted per box with peat in the first decade of May 2021. The butterhead lettuce Omega F_1 variety was grown in the experiment.

Butterhead lettuce was harvested in the second decade of July 2021 (12 July 2021). During test plant vegetation, observations were made for the occurrence of pests, diseases and weeds. Weeds were removed manually during the experiment period in both series. The plants were watered every morning and evening using an adjustable stowage line.

2.2. Peat Sampling and Chemical Analysis

Surface peat sampling (0–30 cm) was conducted after harvesting of butterhead lettuce, then transported to the laboratory, air dried and stored for analysis. The pH of the peat was measured using potentiometric methods with pH meters with electrodes. Measurements with a pH meter in peat suspension using the ratio 1:2 with distilled water were performed after 30 min. Chemical analyses of the peat were performed in an extract of 0.03 M acetic acid, using the universal method according to Nowosielski [34]. The following parameters were determined in the peat substrate before the experiment: salinity with the conductrometric method, total N content with the Kjehdal method, and the content of P, K and Mg in 0.03 N CH_3 COOH extract.

Nutrient content in peat was determined after extraction with acetic acid (0.03 M). P, Mg and $N\text{-}NO_3^-$ content was determined colorimetrically: P with ammonium vanadomolybdate, Mg with the titanium yellow method, and $N\text{-}NO_3^-$ with an ion exchange nitrate electrode. The pH was measured in water suspension (peat to water ratio 1:2) and salinity was assessed using a conductivity meter (the conductivity method).

2.3. Biometric Measurements and Chemical Analysis

Biometric measurements of the test plant were performed, including the biomass and number of test plant leaves. Fresh biomass (g) was determined as an average value from 12 plants. The dry biomass weight was determined by drying samples (specific weight, 200–300 g of fresh mass) at 60 °C for 48 h, then drying them at 105 °C for 4 h.

2.4. Chemical Analysis of Plant Material

After determination of fresh biomass, the leaves were minced for analysis. Chemical analyses were performed in a laboratory belonging to the Horticulture Department of Wroclaw University of Environmental and Life Sciences. Nutrient content in butterhead lettuce and peat was determined after extraction with acetic acid (0.03 M). Phosporus, magnesium, and nitrate nitrogen content in the plant material was determined colorimetrically: P with ammonium vanadomolybdate, Mg with the titanium yellow method, and $N\text{-}NO_3^-$ using an ion exchange nitrate electrode. Uptake of P, Mg and $N\text{-}NO_3^-$ was based on the mass of the plant leaves and the content of these macronutrients. Heavy metal content was determined with the ICP-MS method in a pre-prepared solution with perchloric acid (after sample digestion in 70% $HClO_4$). In the experiment, the presence of heavy metals was determined: Cu, Zn, Pb, Cd and Hg. The selection of heavy metals was based on EU regulations [35]. Mercury was also determined in the plant leaves; however, it was not detectable with the equipment.

2.5. Statistical Analysis

Data from independent biometric features including the mass of plant leaves and number of leaves as well as chemical analyses (P, Mg, N-NO_3^-, Cu, Zn, Cd, Pb) were subjected to Anova/Manova statistical analysis in Statistica software (version 13.1 StatSoft. Poland). The level of significance was α = 0.05. One-way and two-way analyses of variance were performed to determine the effects of horticulture media and P fertilizer on selected butterhead lettuce morphological traits, biomass and chemical content. Homogeneity of the groups was confirmed using a post hoc-test (Tukey test on level 0.05). Names of homogeneous groups were determined from the smallest to the largest value. Standard error (SE) was also added to all measured values.

3. Results and Discussion

3.1. Effect of STR Fertilization on Biometric Traits

A significantly greater number of leaves (18% more than the control and 4% greater than TSP) were found under STR fertilization. Phosphorus fertilization including STR had no significant impact on the fresh mass of plant leaves; neither did different rates of P fertilizer or interaction between these factors. The increased rate of P fertilization significantly increased the number of leaves (Table 2). No significant differences were observed between the examined factors.

Table 2. Effect of various rates of P from STR and TSP fertilizers on selected plant traits.

Fertilization Treatment	Morphological Traits of Butterhead Lettuce	
	Fresh Mass of Leaves (g)	**Number of Leaves**
	P fertilizer (A)	
Control	96 ± 6	10 a ± 0.8
TSP	112 ± 6	12 ab ± 0.3
STR	127 ± 10	12 b ± 0.5
p value	ns	0.05
	Rates of P fertilization (B)	
Control	96 ± 6	10 a ± 0.8
Reduced rate	121 ± 8	12 ab ± 0.4
Recommended rate	112 ± 13	12 ab ± 0.5
Increased rate	126 ± 10	13 b ± 0.5
p value	ns	0.05
A × B	ns	ns

C-control; TSP-superphosphate; STR-struvite; ±SE (standard error); ns—not significant; Means for factors within a column marked with the same letter do not differ significantly at the level α = 0.05.

The results of [20] showed that plant fresh weight was affected by P sources (TSP, STR) and rates of P applied. According to [36], the fresh mass of lettuce increased with an increase in STR dosage from 0.5 to 0.6 g. Under STR fertilization, the average biomass of *Spinacia oleracea* was about twice as large than for the control (unfertilized) pots in the research by [37]. In contrast to our research, TSP and STR produced similar maize yield in a study by [38].

3.2. Effect of STR Fertilization on Content and Uptake of Selected Elements

Struvite fertilization contributed to an 83% increase in P content compared to the control and 13% compared to TSP, as well as increases in P uptake of 142% and 32%, respectively. A similar tendency was observed in nitrate nitrogen (N-NO_3^-) content and uptake. The application of different P rates contributed to the differentiation of P and N-NO_3^- content and uptake by the test plant. In the case of P content and uptake by butterhead lettuce, a reduced rate of P led to a significant increase. In turn, the increased rate of P contributed to a significant increase in N-NO_3^-. Neither P fertilization, nor the rates of this element caused a significant change in Mg content and uptake by butterhead lettuce (Table 3). Significant differences were found in the content and uptake of the tested elements in terms of interaction (Figures 1–6). Struvite fertilization, especially the increased rate, led to a significant increase in P content compared to reduced and recommended rates, as well as TSP in a reduced rate (Figure 1). In terms of P uptake, all rates of STR were beneficial (Figure 2). In the case of Mg (Figure 3), the highest content was found with the increased TSP rate and a reduced STR rate. A significant uptake of this element was demonstrated with the increased TSP rate (52 mg). In the case of N-NO_3^-, the greatest content and uptake were observed using the increased STR rate (Table 3).

Table 3. Effect of TSP and STR fertilization on P, Mg and N-NO_3^- content and uptake by butterhead lettuce.

Fertilization Treatment	Plant Chemical Composition					
	P Content (mg 100 g^{-1} DM)	**P Uptake (mg Per Mass of Leaves)**	**Mg Content (mg 100 g^{-1} DM)**	**Mg Uptake (mg Per Mass of Leaves)**	**N-NO_3^- Content (mg 100 g^{-1} DM)**	**N-NO_3^- Uptake (mg)**
P (A)						
Control	121 a ± 10	11 a ± 1.0	178 ± 22	17 ±2.1	135.6 a ± 14	13.2 a ± 1.4
TSP	195 b ± 15	21 b ± 1.3	157 ± 59	20 ± 7.9	225.3 ab ± 36	26.0 a ± 4.7
STR	221 b ± 6	28 c ± 0.6	147 ± 31	19 ± 4.3	309.5 c ± 29	38.9 b ± 3.0
p value	<0.01	<0.001	ns	ns	<0.05	<0.01
Rate of P fertilization (B)						
Control	121 a ± 10	11 a ± 1.0	178 ± 22	17 ± 2.2	136.6 a ± 14	13.2 a ± 1.4
Reduced rate	228 b ± 13	27 b ± 1.2	129 ± 50	16 ± 7.3	254.6 ab ± 20	30.1 ab ± 0.5
Recommended rate	200 b ± 11	22 b ± 2.3	91 ± 31	11 ± 4.0	191.0 a ± 50	22.0 a ± 6.6
Increased rate	196 b ± 18	24 b ± 1.8	237 ± 66	30 ± 9.3	356.6 b ± 26	44.7 b ± 2.4
p value	<0.01	<0.001	ns	ns	<0.05	<0.01

±SE (standard error); ns—not significant; Means for factors within a column marked with the same letter do not differ significantly at the level α = 0.05.

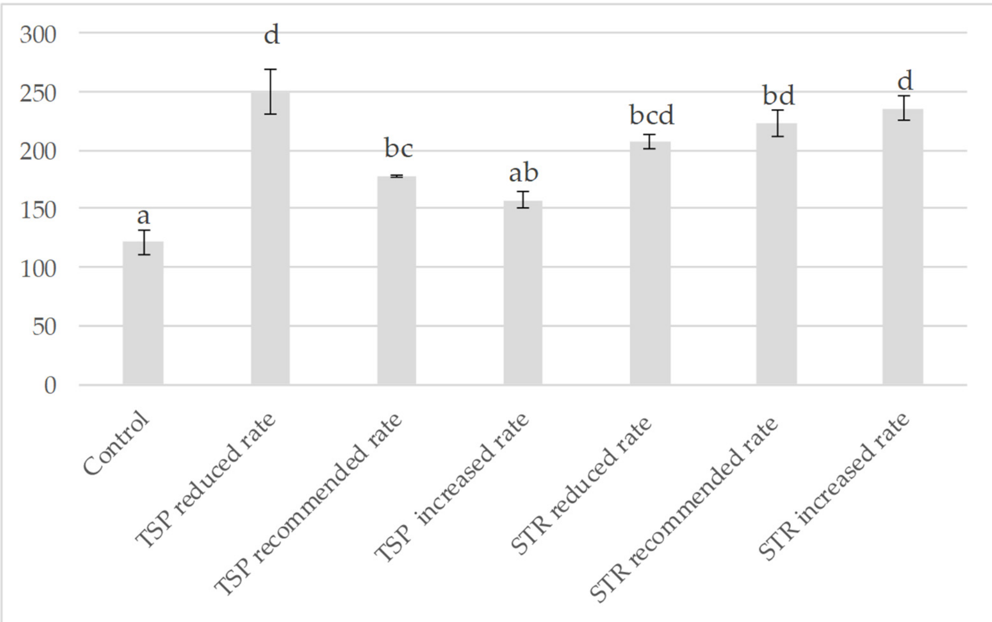

Figure 1. Phosphorus content in butterhead lettuce leaves (mg kg^{-1} DM) as affected by interaction of examined factors (A × B) at the level of significance α = 0.05 (p value < 0.001).

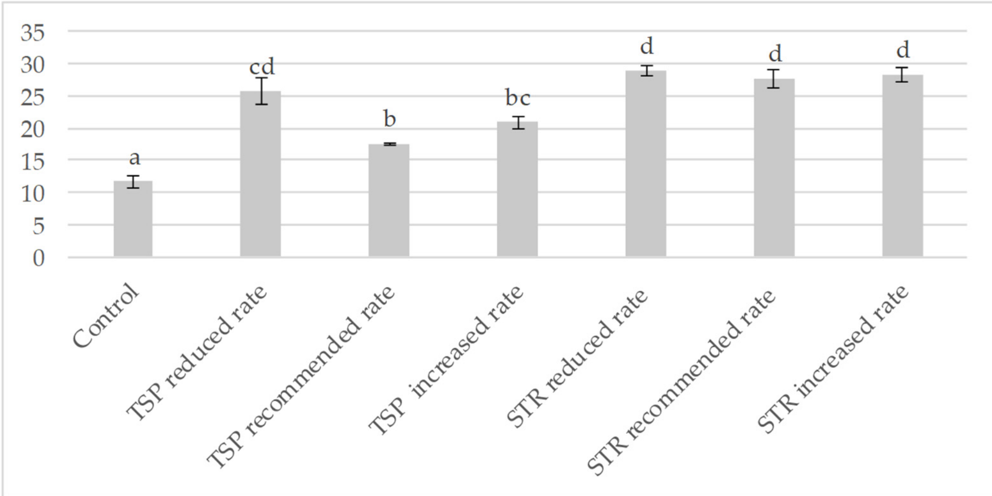

Figure 2. Phosphorus uptake by butterhead lettuce leaves (mg) as affected by the interaction of examined factors (A × B) at the level of significance α = 0.05 (p value < 0.05).

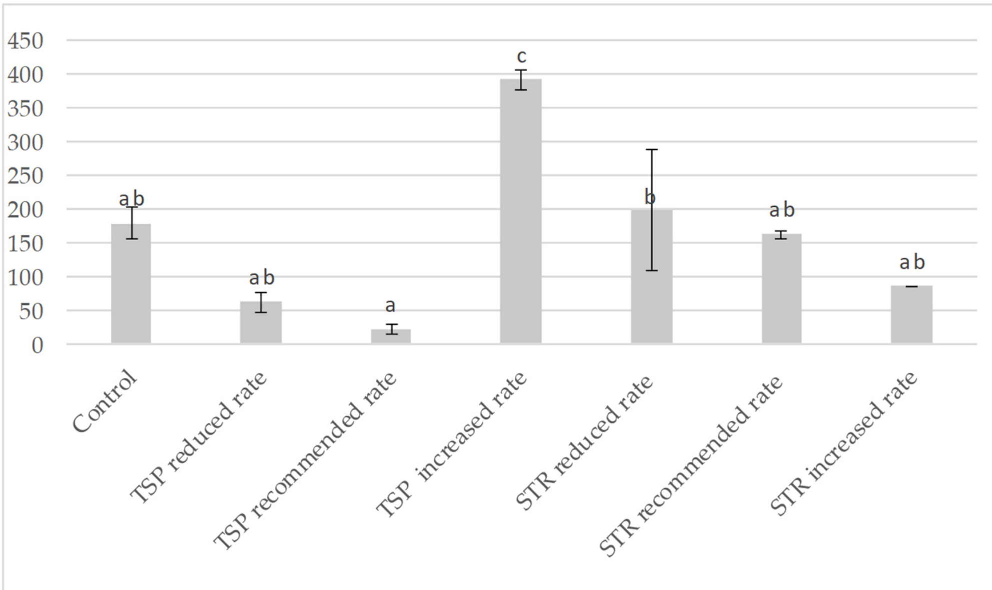

Figure 3. Magnesium content in butterhead lettuce leaves (mg kg^{-1} DM) as affected by the interaction of examined factors (A × B) at the level of significance α = 0.05 (p value < 0.001).

In accordance with [20,39], P and Mg uptake was significantly dependent on P fertilization, whereas the P rate had no significant impact on lettuce. In turn, lettuce leaves with STR had relatively high P and Mg concentrations in a research by [39] as well as in our pot experiment in the case of P. In the case of Mg, STR had no significant impact on the content and uptake of Mg. Similar to our research, control pots had the lowest concentrations of P and Mg compared to the other pots [39]. In our research, P uptake was significantly affected by P fertilization and P ratios. In the study [20], interactions between P source and block, and P rate and block were not significant in nutrient uptake, unlike in our research. In our research, however, this situation concerned the Mg content and uptake. According to these authors, nutrient uptake increased significantly with increasing P rates in the form of both TSP and STR. In our study, only in the case of P and N-NO_3^- did different rates of P fertilizer cause significant differences in the content and uptake of P and N-NO_3^-. The authors of [20] observed that a STR rate of more than 4 mg kg^{-1} enhanced Mg uptake to a significantly greater extent than TSP did, unlike in our experiment. Phosphorus uptake by butterhead lettuce was much higher with STR compared to TSP. These effects, as reported by [20], may be connected to the larger amount of Mg incorporated with STR and the synergistic effect on P uptake. Magnesium is the part of the chlorophyll molecule essential for photosynthesis, activation of plant enzymes needed for growth, and transport of P within the plant [40,41]. A lot of research indicates that increasing Mg levels may lead to increased absorption of P by plants, and vice versa [42–44].

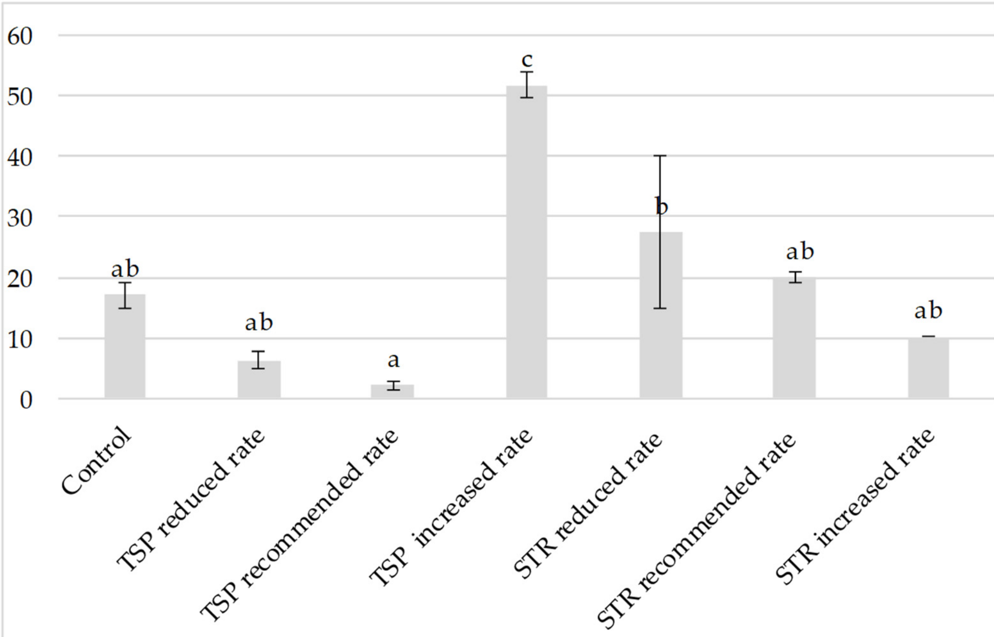

Figure 4. Magnesium uptake by butterhead lettuce leaves (mg per leaves mass) as affected by the interaction of examined factors (A × B) at the level of significance α = 0.05 (p value < 0.001).

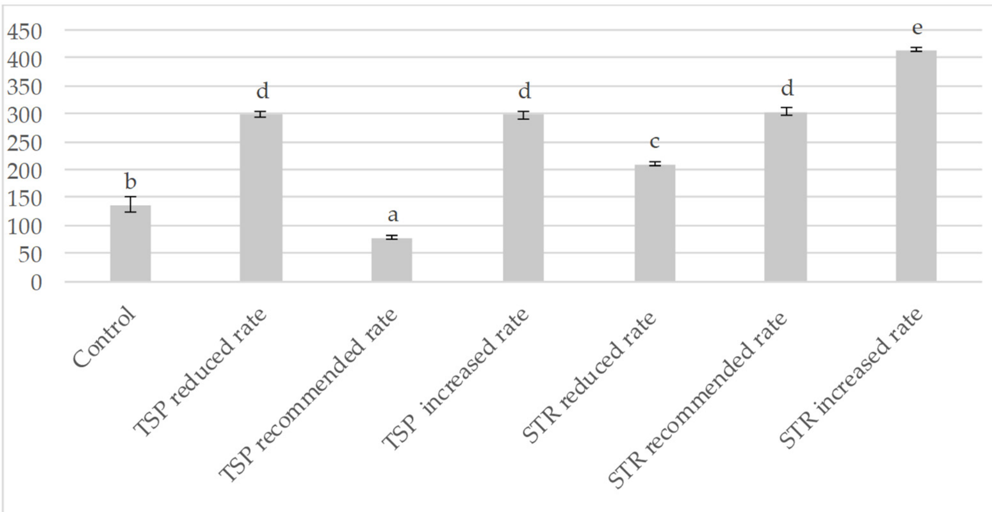

Figure 5. Nitrate nitrogen content in butterhead lettuce leaves (mg kg^{-1} DM) as affected by the interaction of examined factors (A × B) at the level of significance α = 0.05 (p value < 0.001).

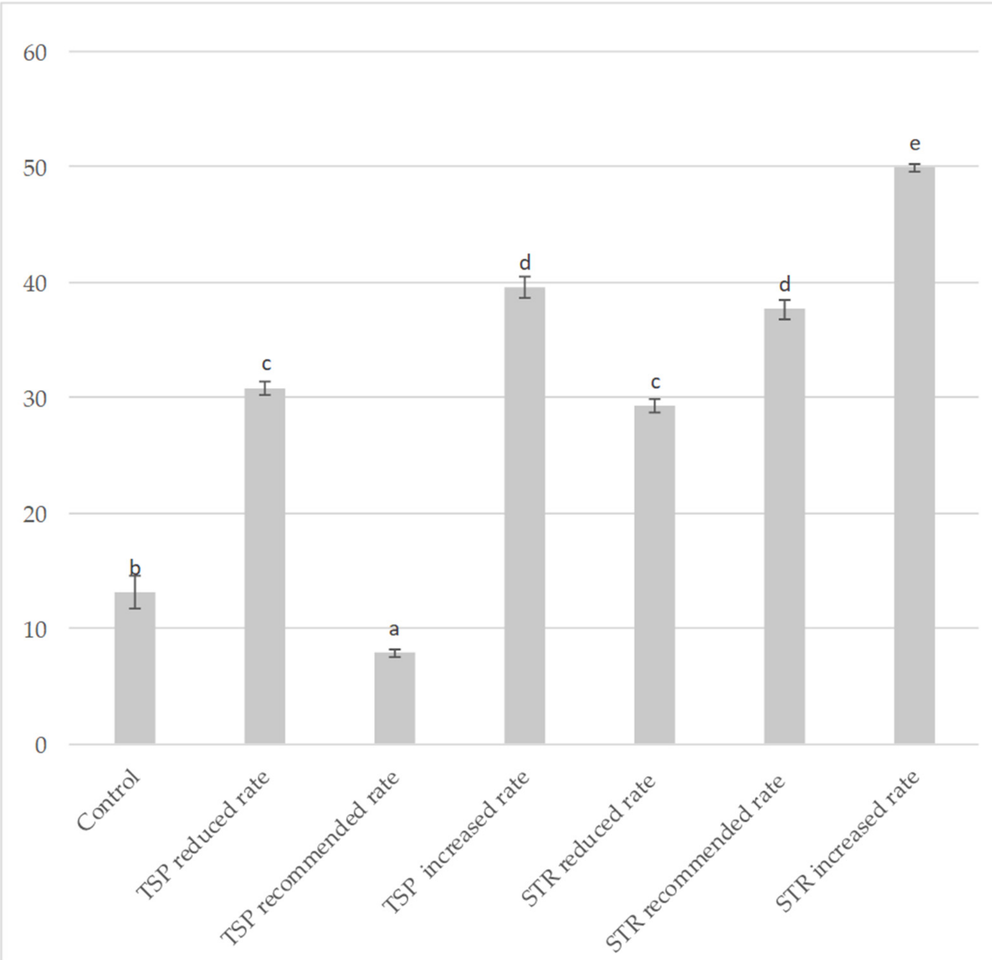

Figure 6. Nitrate nitrogen uptake by butterhead lettuce leaves (mg per leaves mass) as affected by the interaction of examined factors (A × B) at the level of significance $\alpha = 0.05$ (p value < 0.001).

Nitrate nitrogen content of vegetables is dependent on many factors, such as fertilizer use, soil properties, cultivation and weather conditions [45,46]. In our research, a high amount of $N\text{-}NO_3^-$ was found in butterhead lettuce under STR cultivation and following the application of the increased rate of P fertilization; therefore, fertilizer use had a significant impact on the content and uptake of $N\text{-}NO_3^-$. According to [47], variation in the P fertilizer rate had no effect on $N\text{-}NO_3^-$ accumulation in beet and spinach. In study [37], $N\text{-}NO_3^-$ content was below 0.9 g kg^{-1} for spinach fertilized with STR, which is well below the threshold value set by the EU regulations (European Commission 2011). In our research, $N\text{-}NO_3^-$ content increased under STR fertilization; however, the content was also within the acceptable value. On the basis of the regulation of 2 December 2011 amending Regulation (EC) No. 1881/2006 regarding maximum levels for $N\text{-}NO_3^-$ in foodstuffs, its content did not exceed permissible concentrations in lettuce [48]. Similar to the above experiment, Wang and Li (2004) [49] showed clear and significant differences in $N\text{-}NO_3^-$ concentrations between P fertilization and non-fertilization for cabbage, green cabbage and oilseed rape in the second term of sampling, as was the case in our study. The effect of P fertilizer on $N\text{-}NO_3^-$ accumulation varies according to vegetable species and sampling date.

3.3. Effect of STR Fertilization on P and Mg in Peat

Struvite fertilization led to a significant pH increase, as did different rates of P fertilization. Significantly higher pH was noted under a recommended rate of P fertilization. The opposite tendency was found for peat salinity, with the lowest value under STR fertilization, without significant differences related to various rates of P fertilization. The reduced rate of TSP fertilization led to an increase in the salinity of the peat. A significant increase in P content in the peat was observed under STR application compared to the control. The highest rate of P caused a significant enhancement of P content in the peat. The greatest rate of STR application contributed to the largest P content in the peat (Table 4). Magnesium content was dependent on the rates of P fertilization, with the highest value being noted with an increased rate of P fertilizer. The most beneficial strategy for Mg content in peat was also the increased rate of STR.

Table 4. Effect of STR fertilization on P, Mg and nitrate ($N\text{-}NO_3^-$) content in peat substrate.

Fertilization Treatment	Chemical Composition of Peat Substrate				
	pH	**Salinity (mS cm^{-1})**	**P (mg dm^{-3})**	**Mg (mg dm^{-3})**	**N-NO$_3^-$ (mg dm^{-3})**
		P fertilizer (A)			
Control	5.2 a ± 0.1	1257 ab ± 12	23 a ± 1.2	32 ± 1.2	5.4 a ± 2.1
TSP	5.7 b ± 0.1	1185 b ± 104	123 ab ± 20	38 ± 9.9	3.1 a ± 1.5
STR	5.8 b ± 0.1	846 a ± 80	143 b ± 22	58 ± 10	50.1 b ± 4.8
p value	<0.001	<0.01	<0.01	ns	<0.01
		Rates of P fertilization (B)			
Control	5.3 a ± 0.1	1257 ± 12	23 a ± 1.2	32 ab ± 1.2	5.4 ± 2.1
Reduced rate	5.8 bc ± 0.1	950 ± 230	80 b ± 5.5	25 a ± 7.5	2.7 ± 3.2
Recommended rate	5.8 c ± 0.1	953 ± 11	106 b ± 13	47 ab ± 12.4	36.2 ± 2.4
Increased rate	5.6 b ± 0.1	1143 ± 31	214 c ± 5.8	73 b ± 10.9	41.0 ± 12
p value	<0.001	0.41	<0.01	<0.05	ns
A × B	ns	<0.01	<0.01	ns	<0.001

±SE (standard error); ns—not significant; Means for factors within a column marked with the same letter do not differ significantly at the level $\alpha = 0.05$.

Phosphorus fertilization, especially with STR, caused significant changes in $N\text{-}NO_3^-$ content in the peat. Interactions between the examined factors also led to significant changes in $N\text{-}NO_3^-$ content in the peat. Significant changes were found following STR fertilization with recommended and increased rates (Figures 7–9).

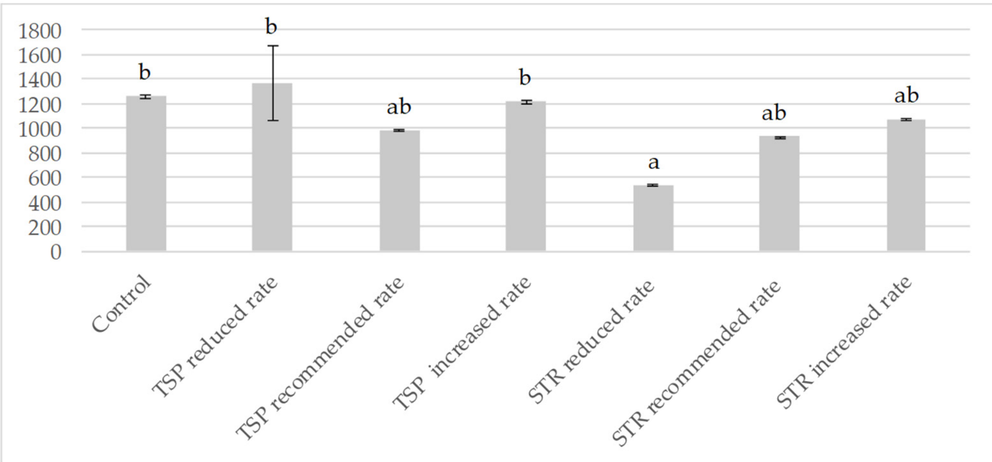

Figure 7. Salinity (mS cm^{-1}) as affected by the interaction of examined factors (A × B) at the level of significance $\alpha = 0.05$ (p value < 0.01).

It was found by [50,51] that the effectiveness of STR as a P fertilizer depends on soil properties. This thesis is consistent with the results obtained in this study. In turn, substrate pH in the experiment in [51] was significantly influenced by treatments with P, as was the case in our own study. Our literature survey produced three field scale experiments, on which basis it can be concluded that available P after STR application increased [52,53] but did not show differences, unlike in pot experiments. In our experiment, available P content increased significantly under STR fertilization. In the soils tested in the experiment in [54], Mg uptake was significantly higher after STR application. It was also found by these authors that the content of residual P and Mg in all post-harvest soils was not significantly affected by STR content, which contrasted with the results of our experiment.

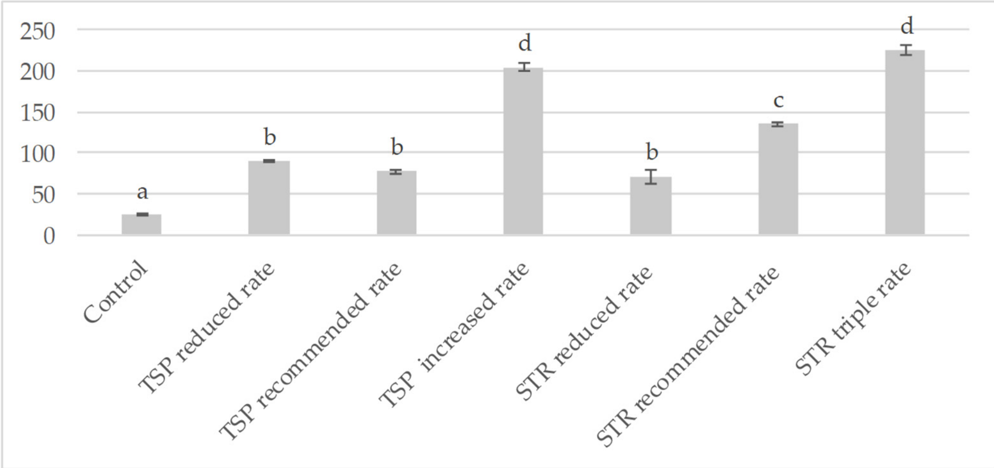

Figure 8. Phosphorus content in the peat (mg dm^{-3}) as affected by the interaction of examined factors (A × B) at the level of significance α = 0.05 (p value < 0.01).

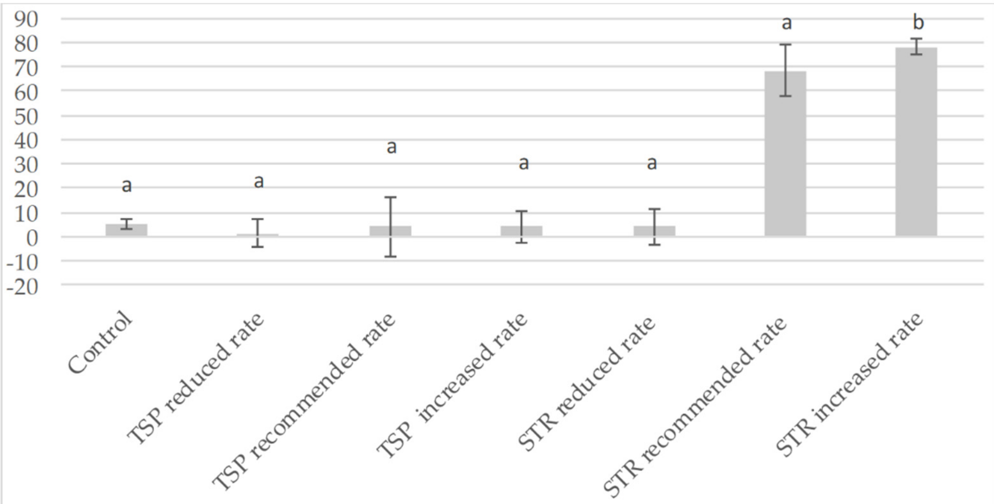

Figure 9. Nitrate nitrogen content in the peat (mg dm^{-3}) as affected by the interaction of examined factors (A × B) at the level of significance α = 0.05 (p value < 0.001).

According to [55], NP application significantly increased the N-NO_3^- content of soil in the 0–60 cm layer. In our study, P fertilization also increased the N-NO_3^- content, especially after STR fertilization. There was a significant difference in N-NO_3^- accumulation between P and non-P applications when fertilizer N reached a certain level. A higher amount of N applied would lead to a lower accumulation of N-NO_3^- after P application [49].

3.4. *Effect of STR Fertilization on Heavy Metal Content in Plants and Peat*

Phosphorus fertilization only had an impact on the Zn content in plant leaves. The lowest amount of this element was noted for STR fertilization (60 mg kg^{-1}). Rates of P fertilization significantly affected Zn and Cd content. The lowest amount of Zn and Cd was observed for the recommended and increased rates of applications (Zn content) and recommended rate (Cd content) (Table 5). Interaction between factors did not significantly affect the heavy metal content of plant leaves. Mercury was also determined in the plant leaves, but its concentration was below the detection limit.

Table 5. Effect of P fertilization on selected heavy metal contents in butterhead lettuce.

Fertilization Treatment	Heavy Metals Content (mg kg^{-1} DM)			
	Zn	Pb	Cd	Cu
		P fertilizer (A)		
Control	100 b ± 11	0.959 ± 0.1	0.5 ± 0.1	4.01 ± 0.2
TSP	67 b ± 5.9	0.982 ± 0.1	0.5 ± 0.1	4.21 ± 0.3
STR	60 a ± 5.3	0.800 ± 0.1	0.4 ± 0.0	3.53 ± 0.2
p value	<0.01	ns	ns	ns
		Rates of P fertilization (B)		
Control	100 b ± 11	0.959 ± 0.1	0.5 ab ± 0.1	4.01 ± 0.5
Reduced rate	79 b ± 6.1	0.924 ± 0.1	0.5 b ± 0.0	3.81 ± 0.4
Recommended rate	54 a ± 4.1	0.868 ± 0.1	0.3 a ± 0.0	3.53 ± 0.3
Increased rate	56 a ± 4.5	0.881 ± 0.1	0.5 ab ± 0.0	4.27 ± 0.4
p value	<0.001	ns	<0.05	ns
A × B	ns	ns	ns	ns

±SE (standard error); ns—not significant; Means for factors within a column marked with the same letter do not differ significantly at the level α = 0.05.

Heavy metals can be a serious problem in an agronomic field when the recovered STR is used as a fertilizer. According to [39], lettuce under STR fertilization did not have such high levels of heavy metal concentration as those seen with other commercial fertilizers. This was also the case in our study where butterhead lettuce cultivation using struvite recovered from swine effluent can be regarded as safe. According to [50], STR showed a level of contamination at least three times lower than the limits set by the German Sewage Sludge Ordinance. The more stringent provisions of the German Federal Soil Protection Act (in the version published on 17 March 1998, Federal Law Gazette I p. 502) were also met if heavy metal loading during periodic fertilization is considered. The author in [37] studied the amounts of heavy metals in the precipitate which were also below the maximum permissible levels set out in EC Directives (Council Directive of 12 June 1986 on the Protection of the Environment, and in Particular of the Soil, When Sewage Sludge Is Used in Agriculture (86/278/EEC)). Similarly in Mahmood et al. (2018) [52], STR from chicken slurry was characterized by low heavy metal content and was therefore suitable for use in field conditions.

Phosphorus fertilization and different rates had a significant impact on Zn, Pb and Cu content in the peat (Table 6). Significantly higher Zn and Cu content was found with STR fertilization while TSP increased Pb content. The greatest Zn and Pb contents were observed with the reduced rate of P fertilization. However, P fertilization had no effect on Cd content in peat; neither did different rates of this fertilizer. In contrast, P fertilization had a significant impact on Cu content in the peat substrate. A significantly higher content of Cu was noted following STR fertilization with reduced and recommended rates (Figure 10).

Table 6. Effect of P fertilization on selected heavy metal contents in the peat substrate.

Fertilization Treatment	Heavy Metals Content (mg kg^{-1} DM)			
	Zn	Pb	Cd	Cu
		P fertilizer (A)		
Control	0.07 a ± 0.0	0.2 a ± 0.0	0.16 ± 0.0	0.58 a ± 0.1
TSP	2.09 b ± 0.2	15.3 b ± 0.8	0.32 ± 0.0	0.88 a ± 0.1
STR	2.36 b ± 0.2	15.2 b ± 0.9	0.80 ± 0.4	1.69 b ± 0.2
p value	<0.001	<0.001	ns	<0.01
		Rates of P fertilization (B)		
Control	0.07 a ± 0.0	0.2 a ± 0.0	0.16 ± 0.0	0.58 ± 0.1
Reduced rate	2.47 b ± 0.2	15.6 b ± 1.2	0.40 ± 0.1	1.76 ± 0.4
Recommended rate	1.93 b ± 0.1	14.5 b ± 1.1	0.32 ± 0.0	0.96 ± 0.2
Increased rate	2.29 b ± 0.2	15.5 b ± 1.1	0.96 ± 0.6	1.13 ± 0.1
p value	<0.001	<0.001	ns	ns
A × B	ns	ns	ns	<0.01

±SE (standard error); ns—not significant; Means for factors within a column marked with the same letter do not differ significantly at the level α = 0.05.

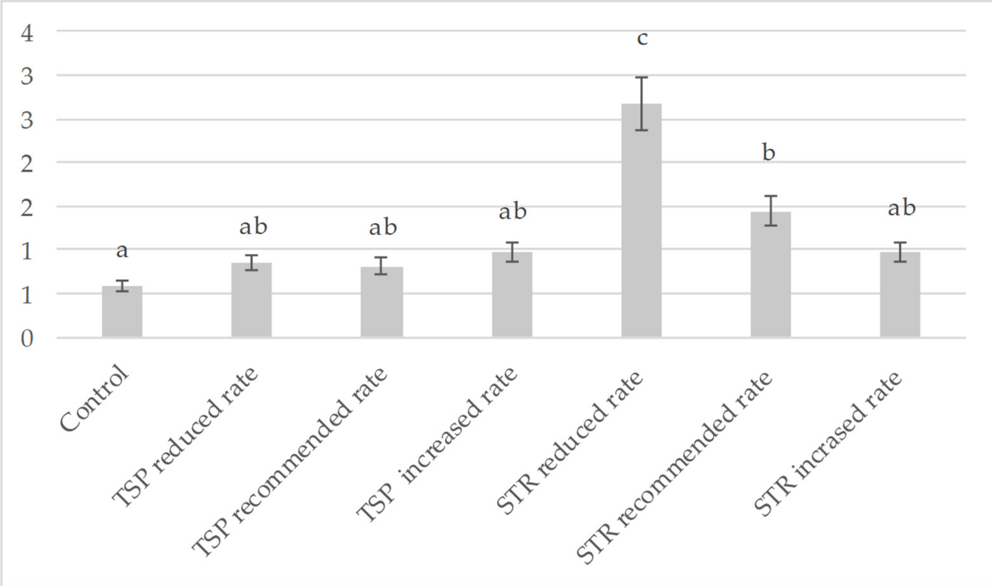

Figure 10. Copper content in the peat (mg kg $^{-1}$ D.M) as affected by the interaction of examined factors (A × B) at the level of significance α = 0.05 (*p* value < 0.01).

Continuous fertilization of soils can cause heavy metal contents to rise above their natural levels in the soil, and the transfer of these metals into the human food chain should not be overlooked. According to the study by [53], some Pb and Zn is relatively weakly bound in peat, probably by complexation on the iron oxide surface and/or the surface of organic matter. On the basis of the study in [54], concentrations of Cd and Pb increased significantly under fertilization. In our study, the concentrations of Pb increased dramatically compared to the concentration of Cd. This may be related to the excessive use of fertilizers. In conclusion, STR has a high commercial value highlighting an important aspect of nutrients as well as low harmful substances [53,55].

4. Conclusions

Our findings indicate that the STR fertilizer Phosgreen based on sewage sludge production is more effective than TSP in increasing the number of butterhead lettuce leaves, P content in the peat and lettuce and uptake. This may be related to the higher amount of Mg incorporated with STR and its synergistic effect on P uptake. In conclusion, the results show that the potential value of STR as a marketable P fertilizer is promising, especially for crops with high P and Mg requirements. The safety of STR results from its low levels of heavy metals, and consequently the low levels in the butterhead lettuce. None of the examined rates of STR caused an increase in heavy metal content in butterhead lettuce leaves. The increased rate of STR was the most beneficial because it led to an increase in P, while all rates of STR brought about an increase in P uptake. Thus, STR appears to be a better P source compared to TSP, which also provides available Mg.

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