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Effect of Different Doses of Phosgreen Fertilization on Chlorophyll, K, and Ca Content in Butterhead Lettuce (*Lactuca sativa* L.) Grown in Peat Substrate

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Abstract: Struvite is regarded as a promising phosphorus (P) fertilizer compared to commercial pristine mineral phosphorus fertilizers. The aim of this study was to determine the effect of Phosgreen fertilizer, with struvite as its phosphorus source, on the chlorophyll, potassium (K), and calcium (Ca) contents in lettuce grown in peat compared to superphosphate. The study was carried out as a pot experiment with different doses of P fertilization. The study presents the chlorophyll a, b, total (a + b) chlorophyll, and carotenoid contents of the lettuce plants. Significant differences in the chlorophyll a and b contents were observed between the different phosphorus applications, and this can have a direct impact on the crop yields. Significantly higher contents of both chlorophyll contents were observed under Phosgreen fertilization as well as the chlorophyll a + b content *. The results of the study on lettuce indicate a dependence of vitamin C content on phosphorus fertilizer, but with no significant increase under Phosgreen fertilization; the contents of K and Ca were not significantly dependent on the type of phosphorus fertilizer. Due to the favorable composition of Phosgreen, it may be recommended for use as a phosphorus fertilizer in the agriculture and horticulture sectors.

Keywords: peat; sewage sludge; Phosgreen; superphosphate; K, Ca uptake and content; chlorophyll content; carotenoids; vitamin C

Citation: Jama-Rodzeńska, A.; Chohura, P.; Gałka, B.; Szuba-Trznadel, A.; Falkiewicz, A.; Białkowska, M. Effect of Different Doses of Phosgreen Fertilization on Chlorophyll, K, and Ca Content in Butterhead Lettuce (*Lactuca sativa* L.) Grown in Peat Substrate. *Agriculture* **2022**, *12*, 788. https://doi.org/10.3390/agriculture12060788

Academic Editor: Markku Yli-Halla

Received: 21 April 2022
Accepted: 29 May 2022
Published: 30 May 2022

1. Introduction

Due to the increased consumption in phosphate fertilizers and the simultaneous depletion of its reserves, attention should be paid to the search for alternative sources of phosphorus in a circular and reusable system based on the sustainability concept [1–3]. The peak demand for phosphorus will probably occur between 2030 and 2040 because phosphorus has been identified as a critical raw material (Critical Raw Materials for the EU) by the EU Minerals Initiative [4,5]. The high dependence of agriculture on phosphorus and, additionally, the growing problem of the eutrophication of inland and coastal waters is stimulating the search for a material that will replace phosphorite [6,7]. Food production chains have led to a renewed and urgent interest in the concept of closing the phosphorus cycle by recovering and recycling phosphorus in a circular economy system [8–10]. Currently, phosphorus management in the agricultural sector is characterized by the so-called open cycle. The closure of this cycle should be based on the introduction of a circular economy using available materials with valuable properties. One such material is sewage sludge, which is currently used for phosphorus recovery [11–13]. The result of the application of technologies for phosphorus recovery is the production of struvite, which, due to its high phosphorus content, low heavy metal content, and lack of microbiological contamination can be used as a phosphorus fertilizer [14–16]. Phosphorus fertilizers produced from recycled materials are based on fertilizers, resulting from the recovery of nutrients in crystallization processes [17]. Commercial mineral phosphorus fertilizers include various phosphorus compounds (substances) such as single superphosphate, triple superphosphate, diammonium phosphate, monoammonium phosphate, calcium superphosphate, or potassium phosphate. Commercial mineral fertilizers are produced from limited phosphate resources (about 80–90% of phosphate rock mined annually is used to produce phosphate fertilizers) [18,19]. However, its natural sources are being depleted in the face of intensive exploitation as a result of demographic and economic factors [5].

Struvite (NH_4 $MgPO_4$ $6H_2O$) is a poorly water-soluble crystal in which 3% of the total phosphorus content is water soluble [20]. Once introduced into the soil, phosphorus fertilizers that contain struvite slowly release phosphorus forms that are available to plants [14,21]. However, this characteristic can, in some cases, lead to reduced plant growth and development, thus affecting yield [21]. Therefore, the amount of phosphorus released from phosphorus fertilizers that have struvite in their composition may not be sufficient for rapid phosphorus uptake, especially during the early stages of plant development [22,23].

So far, several experiments conducted on the application of phosphorus fertilizers that have struvite in their composition have demonstrated positive effects on the yield and chemical composition of vegetable crops (lettuces and cabbage), grasses (Sudan grass), maize, and selected fruits compared to conventional fertilizers [21,24–26]. The magnesium content in phosphorus fertilizers that have struvite in their composition makes this form more effective compared to other fertilizers [20]. So far, there have been no studies into the effect on the chlorophyll, carotenoid, and vitamin C content in the phosphorus fertilizers that contain struvite. The chlorophyll concentration in leaves is an important parameter that is regularly measured as an indicator of the chloroplast content, photosynthetic mechanisms, and plant metabolism [27]. Chlorophylls a and b are the main photosynthetic pigments of plants, and, together with carotenoids, they are part of the photosystem. The chlorophyll content normally exceeds the carotenoid concentrations by up to five times in green vegetables, where its values range from 1000–2000 mg kg^{-1} fresh weight [28]. Fresh fruits and vegetables contain mainly chlorophylls a and b. Thus far, there is no standard or reliable information in the literature about the chlorophyll content of plants under Phosgreen fertilization. Changes in the chlorophyll content depend on the cultivar, plant part, harvest date, and maturity stage. In addition, different extraction and quantification methods can cause inconsistencies in the chlorophyll content [29]. Taiz and Zeiger [30] argue that the presence of chlorophyll in plants is essential for their development. However, when chlorophyll is limited to low concentrations, it directly affects the production and growth of varieties. In turn, calcium contributes to the maintenance of cell membrane stability, wall structure, and its deficiency is related to many disorders, particularly in fruit and storage organs [31].

Our research hypothesis was that fertilization would influence the potassium (K) and calcium (Ca) content and increase the vitamin C and chlorophyll content as well as Ca and K uptake by the test plant.

2. Materials and Methods

2.1. Agrotechnology of the Experiment

The study was carried out as a pot experiment with four replications under greenhouse conditions at the Research and Education Station of Wroclaw University of Environmental and Life Sciences in Psary, belonging to the Department of Horticulture. In the experiment, two phosphorus fertilizers were applied: traditional triple superphosphate (SUP), which is commonly used in the cultivation of butterhead lettuce, and a Phosgreen fertilizer based on sewage sludge. The heavy metal content of the phosphorus fertilizers were presented in an earlier manuscript by Jama-Rodzeńska et al. [21]. The pot experiment under greenhouse conditions was conducted in two series from May to July 2021. The experiment examined the effect of a fertilizer made from sewage sludge with the trade name Phosgreen (produced by KREVOX, which operates under license from the Canadian company OSTARA NUTRIENT TECHNOLOGIES) in comparison with the traditional fertilizer triple superphosphate. This fertilizer was in granule form and its diameter was around 2–3 mm. Granulation influences the rate of dissolution. The Phosgreen fertilizer contains 2% N, 24% P_2O_5, 12% Mg, 0% K, pH 9.2, and is characterized by a low content of heavy metals compared to the triple superphosphate. The triple superphosphate (SUP) used in the experiment was purchased from Ampol Merol (Wąbrzeżno, Poland), which additionally contained lime (10% CaO and 40% mineral phosphates as P_2O_5).

The chemical composition of the deacidified peat used in the experiment was as follows: pH in water 5.6; salinity 1.4 g NaCl dm^{-3}, available N 230 mg dm^{-3}, P 80 mg dm^{-3}, K 230 mg dm^{-3}, and Mg 150 mg dm^{-3}. Before the experiment, the peat was mixed with fertilizers and used as the substrate for the lettuce. This substrate had standard nutrient concentrations and its chemical composition was altered by adding mineral fertilizers to satisfy the nutrient requirements of the lettuce. Before the experiment, the peat substrate was mixed with ammonium nitrate (AN) at a concentration of 122.4 mg L^{-1} and potassium sulfate (SP) at a concentration of 300.0 mg L^{-1} and phosphorus fertilizer: alternative (Phosgreen) and conventional (SUP) at three doses: (1) the recommended dose based on the soil element content and lettuce nutrient needs; (2) reduced dose (50% lower); and (3) increased dose (50% higher than recommended).

The applied rates of the alternative (Phosgreen) and conventional (SUP) fertilizers included:

SUP reduced dose—17 mg L^{-1};
Phosgreen reduced dose—29 mg L^{-1};
SUP Recommended dose—34 mg L^{-1};
Phosgreen recommended dose—57 mg L^{-1};
SUP increased dose—68 mg L^{-1};
Phosgreen increased dose—114 mg L^{-1}.

Unfertilized crops (control) were also grown in the pot experiment. Lettuce seeds were sown in multiples, and at stage 4 of the developed leaves, the lettuce seedlings were transplanted into 12 dm^3 boxes. Four seedlings were planted into each box in the first ten days of May 2021. Butterhead lettuce of the Omega F_1 variety was used in the study. The lettuce was harvested in the second decade of July 2021 (12 July 2021). During lettuce vegetation, observations were made for pests, diseases, and weeds. Plants were watered every morning according to the need to use piped water.

2.2. Peat Sampling and Peat Chemical Analysis

Surface peat samples (0–10 cm) were collected after butterhead lettuce harvest and then transported to the laboratory, air-dried, and prepared for analysis. The measurements of peat pH were performed using the potentiometric method using pH meters with electrodes. The pH-meter measurements in a 1:2 suspension of peat with distilled water were taken after 30 min and the salinity was assessed using a conductivity meter (conductometric method). The potassium (K) and Ca (calcium) contents of peat were extracted with 0.03 M acetic acid solution using the universal method according to Nowosielski (1988) [32].

The following parameters were determined in the peat medium before the experiment: salinity by the conductometric method, total nitrogen (N) content by the Kjehdal method, and the P, K, and magnesium (Mg) content in the 0.03 N CH_3COOH solution [33]. The nutrient content of peat was determined after extraction with acetic acid (0.03 M). The contents of K and Ca were analyzed using flame photometry [33–35].

2.3. Chemical Analysis of Plant Material

After the determination of fresh biomass, the leaves were crushed for analysis. Chemical analyses were carried out in a laboratory belonging to the Department of Horticulture, Wroclaw University of Environmental and Life Sciences. The content of the nutrients in the butterhead lettuce and peat was determined after extraction with acetic acid (0.03 M) [33,34]. The content of Ca and K in the plant material was determined using flame photometry. The uptake of K and Ca was determined based on the plant leaf weight and the content of these macronutrients. The dry weight of lettuce was determined by drying the samples (specific weight, 200–300 g fresh weight) at 60 °C for 48 h and then drying at 105 °C for 4 h [36].

2.4. Chlorophyll Content in Lettuce Leaves

A leaf sample weighing 0.4 g was mixed using a clean pestle and mortar. To this homogenized leaf material, 20 mL of 80% acetone and 0.5 g of powdered $MgCO_3$ were added. The materials were further gently crushed and then shaken for three minutes and automatically extracted with a pump. The supernatant was transferred to a 100 mL volumetric flask and the volume was supplemented by adding 80% acetone. The absorbance of the color of the solution was evaluated using a spectrophotometer at 645 and 663 nm.

Formula [37]:

$$\text{Chl a} = 11.75 \times \text{A662.6} - 2.35 \times \text{A645.6}$$

$$\text{Chl b} = 18.61 \times \text{A645.6} - 3.96 \times \text{A662.6}$$

$$\text{Carotenoids} = (1000 \times \text{A470}) - (3.27 \times \text{Chla}) - (104 \times \text{Chl b})/229$$

where Chl a and Chl b represent chlorophyll a and chlorophyll b, and A is the absorbance.

The chlorophyll content was reported as mg of chlorophyll 100 g^{-1} fresh weight, and the total chlorophyll was calculated as the sum of chlorophyll a and chlorophyll b while the carotenoids were reported in μg 100 g^{-1} FM [37].

2.5. Statistical Analysis

Data from the independent chemical analyses including chlorophyll, carotenoids, Ca, K, and the vitamin C content in the plant and peat (Ca, K) material were statistically analyzed with ANOVA/MANOVA in Stat. (version 13.1 Stat Soft Poland). The significance level was $\alpha = 0.05$.

One-way and two-way analyses of variance were performed to determine the effect of horticultural medium and fertilizers on the chemical composition of butterhead lettuce. The homogeneity of the groups was confirmed using a post hoc test (Tukey's test at the 0.05 level). The names of the homogeneous groups were determined from the smallest to the largest value. The standard error (SE) was also added to all measured values.

3. Results and Discussion

3.1. Effect of P Fertilization on the Chlorophyll and Carotenoid Content in Lettuce Leaves

Phosphorus (P) fertilization had a significant impact on the chlorophyll content: a, b and a + b (total). Phosgreen fertilization caused a significant increase in the chlorophyll content in lettuce leaves, but not in the carotenoid content (Table 1). Significantly higher chlorophyll content was observed under Phosgreen fertilization compared to the SUP.

None of the tested doses caused significant changes in the chlorophyll content or carotenoid content. Interaction between the examined factors also did not lead to significant changes in the chlorophyll and carotenoids.

Table 1. The effect of Phosgreen and SUP fertilization on the chlorophyll content in butterhead lettuce.

Experiment Factor	Chlorophyll Content and Carotenoids			
	Chlorophyll a mg $100g^{-1}$ FM	Chlorophyll b mg $100g^{-1}$ FM	Chlorophyll a + b mg $100g^{-1}$ FM	Carotenoids µg $100g^{-1}$ FM
	Phosphorus fertilizer (A)			
Control	95 a ± 5.5	23 ab ± 1.7	118 a ± 5.6	228± 18.2
SUP	105 a ± 15.4	22 a ± 10.4	127 a ± 18.4	188 ± 13.8
Phosgreen	186 b ± 13.9	46 b ± 27.9	225 b ± 13.9	153 ± 26.5
p value	0.001	0.05	0.001	ns
Doses of P fertilizer (B)	ns	ns	ns	ns
A × B	ns	ns	ns	ns

C—control; SUP—superphosphate; ±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.

Chlorophyll a and chlorophyll b are the primary pigments of plant photosystems [38]. The concentrations of these compounds provide information on the productivity, plant vigor, and environmental quality. In addition, chlorophyll a is the primary photosynthetic pigment in plants and its concentration is 2–3 times higher than secondary chlorophyll b [39]. The quantitative ratio of chlorophyll a to b is usually about 3:1, as presented in our study. Its variation depends on the light regime, the habitat, and the age of the plants. The differences in the chlorophyll contents between P fertilizers may be due to the composition of P fertilizers used to fertilize plants [40]. In the present study, the higher total chlorophyll content recorded in the lettuce fertilized with Phosgreen (that also contains N and Mg) compared to that of the traditional mineral P fertilizer was not fully reflected in the biomass production. Plant growth and yield are complex traits that depend on many factors including light, other nutrients, CO_2, water, variety, and plant enzymatic activity. Therefore, chlorophyll is not the only factor that regulates plant growth and yield. Such experiments with Phosgreen fertilization on chlorophyll content have not been conducted. However, we can conclude that the application of this fertilizer may cause an increase in the chlorophyll a, b, and total content. In Aguero et al. [41], the chlorophyll content of fresh lettuce varied depending on the part of the lettuce: 35.65 ± 1.17, 14.96 ± 2.11 and 3.32 ± 0.99 (in mg chlorophyll/100 g fresh weight) for the outer, middle, and inner zones, respectively, with a 10 times higher content in the outer zone, which is probably due to the greater exposure to sunlight. In our study, the chlorophyll content was much higher than that obtained in Aguero et al. [41]. In contrast, in a study by Xu and Mou [42], the chlorophyll a content under protein hydrolysate treatment ranged from 8.2 to 10.3 mg g^{-1} DW, the chlorophyll b content from 1.4 to 1.9 mg g^{-1} DW, and the total chlorophyll content from 9.6 to 12.2 mg g^{-1}. Many studies have been conducted on the effect of various factors on the chlorophyll content, but the effect of struvite has not been recognized yet [43–45].

3.2. Effect of P Fertilization on Vitamin C, Ca, and K Content in Lettuce Leaves

The vitamin C content was significantly dependent on the P fertilization as well as the interaction between the examined factors (Table 2). Phosgreen fertilization did not significantly change the content of vitamin C in the lettuce leaves compared to the control. Within the fertilization factor, the highest content of vitamin C was found in the variant with SUP, while the lowest was noted in the control and in Phosgreen fertilization. The potassium (K) and calcium (Ca) content as well as their uptake did not depend on phosphorus fertilization. Phosphorus fertilization did not significantly change the content and uptake of these elements in lettuce leaves. A triple dose turned out to be the most beneficial in this case (Table 2). Significantly higher K uptake was observed under SUP and Phosgreen fertilization with a triple dose and calcium under SUP fertilization, also with a triple dose.

Table 2. The effect of SUP and Phosgreen fertilization on vitamin C, K, and Ca content and uptake in butterhead lettuce.

Experiment Factor	Chemical Composition of Lettuce Leaves				
	Vit. C (mg 100 g^{-1} FM)	K Content (mg 100 g^{-1} DM)	K Uptake mg per Mass of Leaves	Ca Content (mg 100 g^{-1} DM)	Ca Uptake mg per Mass of Leaves
			Phosphorus fertilizer (A)		
Control	8.2 a ± 0.3	5625 ± 312.5	541 a ± 30.1	541 ± 41.6	52 ± 4.01
SUP	10.0 b ± 0.4	5226. ± 142.8	589 a ± 38.3	628 ± 80.1	73 ± 12.9
Phosgreen	8.3 a ± 0.4	5321 ± 20 2.7	676 a ± 11.3	538 ± 15.1	68 ± 5.47
p value	0.001	ns	ns	ns	ns
			Doses of P fertilizer (B)		
Control	8.3 ± 0.3	5625 ab ± 312.5	541 a ± 30.1	541 a ± 41.6	52 a ± 4.01
Reduced rate	9.0 ± 0.4	5013 a ± 204.3	599 a ± 15.9	4654 a ± 41.4	55 a ± 5.18
Recommended rate	9.6 ± 1.0	5079 ab ± 188.2	575 a ± 46.6	457 a ± 13.6	52 a ± 3.86
Increased rate	10.1 ± 0.7	5729 b ± 95.8	723 b ± 5.0	827 b ± 54.6	105 b ± 9.09
p value	ns	0.05	0.01	0.001	0.001
			A × B		
Control	8.3 a ± 0.3	5625 b ± 312.5	541 b ± 30.1	542 ab ± 41.6	52 ab ± 4.0
SUP Reduced rate	9.7 abc ± 0.1	547 b ± 0.0	564 b ± 0.0	512 a ± 10.8	53 ab ± 1.1
SUP Recommended rate	12.1 c ± 0.3	4688 a ± 155.8	472 a ± 15.7	429 a ± 4.2	43 a ± 0.4
SUP Increased rate	11.1 c ± 0.3	552 b ± 51.6	731 d ± 6.8	944 c ± 18.3	125 d ± 2.4
Phosgreen Reduced rate	8.3 a ± 0.5	4556 a ± 12.6	635 c ± 1.8	420 a ± 80.0	57 b ± 11.2
Phosgreen Recommended rate	7.6 a ± 0.1	5470 b ± 0.0	678 cd ± 0.0	487 a ± 8.8	60 b ± 1.2
Phosgreen Increased rate	9.2 ab ± 1.5	5937 b ± 0.0	714 d ± 0.0	709 b ± 27.2	85 c ± 3.3
p value	0.05	0.001	0.001	0.001	0.001

C—control; SUP—superphosphate; ±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.

In our study, Phosgreen fertilization did not cause an increase in the vitamin C content of lettuce leaves compared to the control. Similar results were obtained by Plakalovic [46]. In his study, an increase in lettuce fertilization (N 120, P 100, K 120; N 120, P 100, K 120 + 30 g Fitofert 20:20:20/100 m^2/day; N 120, P 100, K 120 + 40g Fitofert 4:10:40/100 m^2/day) had no significant impact on the quality components. The author stated that increased doses of fertilizer did not have a positive effect on the vitamin C content in lettuce, as was also found in our study. Similar results were presented by Premuzic et al. [47] and Govedarica-Lučić et al. [48], who found that N fertilization or fertilization with bio stabilized compost did not change the vitamin C content of lettuce. Similar results were shown in our study. Poulse et al. [49] showed that vitamin C (ascorbic acid + dehydroascorbic acid) content decreased with increased nitrogen supply and also decreased with increased storage time.

Ponce et al. [50] demonstrated that within the same phosphorus dose, phosphorus fertilizer containing struvite contributed to a similar or slightly greater K and Ca uptake for the lettuce compared to the SUP.

According to Hogue et al. [51], increasing the N, P, and K fertilizer rates had no significant effect on the K content in lettuce leaves. In a study by Soundy and Smith [52], it was found that the N and P did not affect the K availability and uptake by plants. In turn, in contrast to the above experiment and our study, the content of K in wheat seed and straw under P and K fertilization significantly differentiated the level of K in grain and wheat straw [53]. Mineral fertilization significantly increased the K content in wheat leaves compared to the control at a location where this element had not been applied for 10 years. The highest K content was found in samples optimally balanced in nitrogen. Both the level of K availability in the soil, which reflects the state of macronutrient reserves, as well as the degree of development of the plant root system are the most important factors in plant K nutrition. In the present study, the lettuce was grown on peat with an average available K content of 230 mg dm^{-3}. The literature data indicate that intensive K fertilization can sometimes cause changes not only in K, but also in other nutrients, resulting in their deficiency or excessive concentrations. This particularly concerns Ca [53].

In the case of calcium, the effect of the fertilization factor is significant only for the content of this component in seed [53].

3.3. Effect of P Fertilization on Ca and K Content in Peat

The calcium (Ca) content in peat was significantly dependent on phosphorus fertilization. Significantly higher Ca content was found under SUP and Phosgreen fertilization compared to the control (Table 3). Significantly, the highest Ca content was observed using reduced and recommended doses of P fertilizer (Table 3). Application of Phosgreen in the recommended dose caused a significant increase in the Ca content in the peat. The potassium (K) content was also dependent on all of the examined traits in the experiment. Phosgreen as well as SUP led to a decrease in this element. None of the mentioned doses caused an increase in the K content in the peat. Interaction between the examined factors led to a significant decrease in the K content in the peat. The greatest K:Mg ratio was found with the control while a decreasing tendency was observed after phosphorus fertilization and when using different doses. The opposite tendency was observed in the case of the Ca:Mg ratio, where phosphorus fertilization led to an increase in this ratio, as did different doses of the fertilizers.

Table 3. The effect of SUP and Phosgreem fertilization on the K and Ca content in peat.

Experiment Factor	Chemical Composition of Peat				
	K Content mg dm^{-3}	**Ca Content mg dm^{-3}**	**Mg Content mg dm^{-3}**	**K:Mg Ratio**	**Ca:Mg Ratio**
	Phosphorus fertilizer (A)				
Control (C)	1716 b ± 16.6	399 a ± 20.3	32 ± 1.2	54	12
SUP	65 a ± 8.5	1126 b ± 67.3	38 ± 9.8	1.71	43
Phosgreen	56 a ± 20.8	936 b ± 142.8	58 ± 10.4	0.96	23
p value	0.001	0.01	ns	-	-
	Dose of P fertilizer				
Control	1716 b ± 16.7	397 a ± 20.3	32 ab ± 1.2	54	12
Reduced rate	58 a ± 9.8	1052 b ± 31.6	25 a ± 7.5	2.3	54
Recommended rate	58 a ± 11.4	1247 b ± 125.1	47 ab ± 12.4	1.2	31
Increased rate	65 a ± 15.3	793 ab ± 166.6	73 b ± 10.8	0.9	13
p value	0.001	0.01	0.05	-	-
	A × B				
Control	1716 ± 16.7	399 a ± 20.3	32 ± 1.2	54	12
SUP Reduced rate	79 b ± 4.3	1120 b ± 7.3	15.3 ± 1.8	5.2	75
SUP Recommended rate	83 b ± 4.3	1093 b ± 229.2	51 ± 27.3	1.67	31
SUP Increased rate	32 a ± 1.0	1163 b ± 25	49 ± 2.6	0.7	23
Phosgreen Reduced rate	36 a ± 2.7	983 b ± 16.6	36 ± 13.0	1.0	34
Phosgreen Recommended rate	33 a ± 1.7	1401 b ± 44.7	42 ± 1.1	0.8	33
Phosgreen Increased rate	99 b ± 7.4	423 a ± 38.4	97 ± 2.4	1.0	4
p value	0.001	0.001	ns	-	-

C—control; SUP—superphosphate; ±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.

According to Kopeć and Gondek [54], the bioavailable K content in soil from different sources differs significantly. The highest amount of this element was observed in soil amended with farmyard manure, while the lowest was noted after the application of sewage sludge. There was also considerable variation in the content of bioavailable forms of K in the soil between years. Based on their study, it can be concluded that on average, the content of available K in soil after the application of sewage sludge is lower in the soil enriched with mineral salts (NPK). In the present study, the K content in the peat depended significantly on the P source and was lower than that in the controls. The contents of available K and Ca in growing medium fertilized with both SUP and Phosgreen were similar, as was the case in Gonzalez-Ponce et al. [50] As the dose of SUP and Phosgreen increased, the content in the available K and Ca remained constant in these studies. In our research, an increase in the doses of P fertilizer caused a significant decrease in these elements. According to Fotyma [55], the K content depends on the pH of the soil. Soil acidity (pH) plays an important role in the release of K from minerals and its leaching under favorable conditions at lower levels. According to Kucher [56], the content of mobile forms of K was the highest at pH 2.8. In Arcas-Pilz et al. [57], the nutrient content in the perlite slowly increased over the period of the harvest, while the P content in phosphorus fertilization containing struvite treatments fluctuated and slowly decreased due to struvite dissolution, similar to the findings of our study.

According to Hogue et al. [51], the K content in soil under different NPK fertilization regimes ranged from 94.5 to 148.8 mg kg^{-1}. The highest K content was observed under increased doses of P and K fertilization, as was noted in our study with phosphorus fertilization.

To determine the nutrient status, different authors have reported different K:Mg thresholds for different soils. During a study on the fertilizer requirements in German soils, the K:Mg values used by Loide [58] were 2:1 (sandy soil), 1.8:1 (sandy loam soil), 1.7:1 (clay soil), 1.2:1 (loam soil), and 3.6:1 (peat soil). Hannan [59] suggested that the K:Mg concentration should be between 0.40 and 0.50, regardless of the soil texture, to avoid Mg-induced K deficiency. Potassium (K) availability does not depend only on the K content of the soil, but also on the relative amounts of other cations (Ca, Mg, and K). Therefore, to investigate nutrient antagonism and ensure the sufficient supply of each nutrient, the relative proportion of cations (Ca, Mg, K) versus the rating of a single cation (e.g., K) to be identified has been suggested [60].

A favorable ratio Ca:Mg is required for optimal plant growth. Many publications have addressed this issue in the literature; however, few papers have discussed struvite fertilization. Bear and Toth [61] reported on the ratios of various cations in the exchangeable material in ideal soil, and suggested that the Ca:Mg ratio should be 6.5:1. In our study, the ratio of Ca:Mg under Phosgreen fertilization was 23:1, while under SUP, the ratio was 43:1, far exceeding the values recommended for peat.

Potassium (K) deficiency in soils with optimal amounts of exchangeable K may be associated with a disproportionate amount of calcium (Ca^{2+}) and/or magnesium (Mg^{2+}) relative to K [62]. According to Hoskins [62], there is usually an inverse and adverse relationship between a very high concentration of one cation in the soil and the availability and uptake of other cations by the plant. This means that if Ca and/or Mg dominate the exchange complex over K, this can limit the K availability, and potentially lead to K deficiency.

4. Conclusions

Three main conclusions can be drawn from the present experiment that allow for the use this fertilizer in horticulture. The first concerns the effect of Phosgreen on chlorophyll as an element, which has an impact on the yield and productivity. Second, a higher level of vitamin C, a nutrient necessary for human health, can be noted under Phosgreen fertilization. This regime also led to a higher uptake of Ca and K by the lettuce and its content in the peat compared to the use of SUP. As a sludge fertilizer, Phosgreen significantly increased the chlorophyll content, which can be connected with a higher mass of lettuce leaves, but this has not been proved statistically in previous research. Phosgreen did not significantly increase the vitamin C content. However, the application of Phosgreen in a triple dose increased the vitamin C levels compared to the control. Third, the uptake of K and Ca did not depend significantly on the fertilization with Phosgreen because this fertilizer does not contain these elements in its composition. However, the addition of Phosgreen significantly increased the Ca content in peat compared to the control. The level was the same as that noted with SUP fertilization.

Author Contributions: Conceptualization, A.J.-R. and B.G.; Data curation, A.S.-T.; Formal analysis, P.C.; A.F.; M.B.; Investigation, A.J.-R., P.C. and B.G.; Methodology, A.J.-R. and P.C.; Project administration, P.C.; A.F.; M.B.; Resources, A.S.-T. and A.J.-R.; Software, A.J.-R., B.G. and A.S.-T.; Supervision, A.J.-R., P.C. and B.G.; Visualization, A.S.-T. and A.J.-R.; Writing—original draft, A.J.-R.; Writing—review & editing, P.C., B.G. and A.S.-T. All authors have read and agreed to the published version of the manuscript.

Funding: The APC/BPC was financed/co-financed by Wroclaw University of Environmental and Life Sciences and by the National Centrum of Science DEC- 2022/06/X/ST10/00047.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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