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Biological Absorption of Chemical Elements in Topinambur Plants by Separation of Wastewater in Podzol Soil

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ABSTRACT

The application of sewage sludge as a fertilizer in podzols soil ambiguously affects the peculiarities of the accumulation of certain chemical elements in various organs of the Jerusalem artichoke plants. Experimental factors in the study were different doses of sewage sludge from sludge maps of wastewater treatment plants and its compost with cereal straw, included together with the compensatory dose of mineral fertilizers to the norm $N_{90}P_{90}K_{90}$ in the Jerusalem artichoke plantation. Determination of the content of chemical elements in soil and plants was carried out by X-ray fluorescence analysis. According to the results of research, it was established that the change of mineral nutrition conditions of Jerusalem artichoke causes significant changes in the chemical composition of its tubers and vegetative mass. Studies have shown a clear positive effect of increasing doses of SS on increasing the content in tubers: K – to 7.9%, Ca – to 1.9, Fe – to 1.9, in green mass: O – to 31.8%, K – to 31.6, Ca – to 24.9, Mg – to 5.9, Mn – to 0.7, Fe – to 0.4 and K – to 34.5%. The coefficients of biological absorption for most chemical elements are more than 1, but for O, Al, Si, Fe, these figures were less than 1. Regression models of phosphorus, potassium, calcium and magnesium content in the vegetative mass of Jerusalem artichoke indicate a high and moderate dependence of these indicators on their content in Jerusalem artichoke tubers and soil.

Keywords: Jerusalem artichoke (*Helianthus tuberosus*); sewage sludge; biological uptake; correlation-regression analysis.

INTRODUCTION

Jerusalem artichoke is a crop with great potential of diverse use (Linxi Yang et al., 2015; Long X. et al., 2016). Jerusalem artichoke or pear (*Helianthus tuberosus* – tuberous sunflower) is a tuberous plant of the genus Asteraceae. Due to low requirements for growing conditions, high intensity of carbon sequestration and synthesis of biomass, inulin, Jerusalem artichoke is considered as selectivity crop for bioethanol production with the added advantage of biologically valuable crop products, which has great potential for use in bioenergy and low-yielding (Murtić S. et al., 2021; Lopushniak & Hrytsuliak, 2021). The main characteristic of Jerusalem artichoke (*Helianthus tuberosus*) is its high ecological plasticity and stress resistance under the conditions of dynamic climate change, which are increasingly manifested by the phenomena of aridization in different climatic zones. (Kalenska et al., 2019; Litvinov et al., 2020; Trnka M. et al., 2021). Numerous studies note the increased response of the culture to the improvement of mineral nutrition under different soil structure and special climatic conditions (Long Xiao-Hua et al., 2010; Sawicka et al., 2021**)**.

Researchers are primarily concerned with changes in the content of inulin, which is one of the most valuable compounds in *Helianthus tuberosus*, due to changes in chemical composition (Sawicka et al., 2021, Lopushniak,.2011), content of biologically active compounds and technological qualities of plant raw materials, including tubers (Linxi Yang, 2015; Sobol et al., 2020).

The assimilation of individual elements of mineral nutrition by *Helianthus tuberosus* differs significantly (from 2.8 to 4.5 times) even in various varieties, which indicates a significant dependence of this process on biological growing conditions (Izsáki & Kádi, 2013). It was indicated that with the introduction of phosphorus-potassium fertilizers, the chemical composition of the vegetative mass of Jerusalem artichoke (*Helianthus tuberosus*) plants changed more depending on the variety, and less on the level of mineral nutrition (Sawicka B. et al., 2015). The high content of Ca, Mg, K in Jerusalem artichoke tubers, which exceeds their content in legumes and cereals was noted (Bobrivnyk L. et al., 2017).

The use of fertilizers, in particular organic, significantly affects the yield, chemical composition of tubers and aboveground mass of *Helianthus tuberosus*. In particular, the application of 15 t/ha of manure and spraying the culture with humic acids provides high productivity, increasing the content of NPK (Mohamed H.E., 2020). Given the significant shortage of manure as an organic fertilizer and its primary use in agriculture in many priority food crops, it is necessary to look for new types of organic fertilizers, such as sewage sludge (SS) (Lamastra et al., 2018; Skrylnyk et al., 2020).

It is known that the use of SS contributes to a significant improvement in agromorphological characteristics, as well as increases productivity, quantity and weight of fruits of cultivated crops (Eid E.M. et al., 2021; Skrylnyk et al., 2020). The use of SS for *Helianthus tuberosus* has increased crop yields, improved crop structure elements, increased nitrogen, phosphorus and potassium in eutric podzoluvisols (Lopushniak & Hrytsuliak, 2021; Lopushniak et al., 2022).

The purpose of the study was to assess the level of impact of various forms of fertilizers, including mineral and non-traditional types of organic fertilizers – SS and composts with this organic material and straw of cereals, on the elemental status of Jerusalem artichoke (*Helianthus tuberosus*), as well as to determine the features of the accumulation of individual nutrients in the tubers and the vegetative mass of this culture.

MATERIALS AND METHODS

The research was conducted in the Precarpathian region of Ukraine. The soil of the research area is podzols soil. The SS used was taken from the sludge overflow maps of Ivano-Frankivsk aeration station. The total area of the research site is 63.0 m^2, the accounting area is 35.0 m^2.

The scheme of the experiment included: option 1 – control; option 2 – application of NPK at a rate of 60 kg/ha in the active substance; option 3 – application of NPK at a rate of 90 kg/ha in the active substance; the remaining options (4–8) provided for the application of SS and composts based on it in different norms with a compensatory dose of mineral fertilizers in terms of the general norm $N_{90}P_{90}K_{90}$, namely: option 4 – dose of SS 20 t / ha + $N_{50}P_{52}K_{74}$; option 5 – dose of SS 30 t/ha + $N_{30}P_{33}K_{66}$; option 6 – dose of SS 40 t / ha + $N_{10}P_{14}K_{58}$; option 7 – compost at a dose of 20 t / ha + $N_{50}P_{16}K_{67}$; option 8 – compost at a dose of SS 30 t / ha + $N_{30}K_{55}$. Composting (SS + straw in the ratio (3:1) was carried out for three months in close proximity to the experimental field.

Organic and mineral fertilizers were applied in spring, just before planting. Added into the soil with a disc harrow to a depth of 25–27 cm, with mineral P and K used before planting crops, and nitrogen N in early spring fertilization.

Field soil and plant samples

The soil samples were taken at a depth of 0–30 cm, and green mass and tubers at the end of the growing season before harvest, which in the experiment was the period of late September – early October, depending on weather conditions (difference in research years did not exceed 7–9 days).

Physicochemical analysis of soil and plant samples

The studies of the elemental composition of soil and plants were performed in one sample by X-ray fluorescence analysis on an EXPERT 3L analyzer. The volume of the test sample was about 0.5 cm^3. The research results were presented in the order of placement of elements in the periodic table to Fe. The absence of chemical elements in the list indicates that the change in its content according to the options of the experiment is insignificant.

In certain samples, the coefficient of biological absorption (CBA) was calculated by the formula:

$$\mathrm{Cba} = \frac{Lx}{Nx} \quad (1)$$

where: Lx – element content in the plant, mg/kg;
Nx – element content in soil, mg/kg.

All experimental measurements were performed in at least four replicates, and the results were presented as the mean Correlation-regression analysis was performed using the STATISTICA 6.0 software package in four replicates.

RESULTS AND DISCUSSION

Changes in the content of mineral nutrients in the soil occurred at different rates of SS. The soil profile of the experimental site is characterized by a clear division of the colloidal fraction, which causes a significant expression of eluvial and illuvial horizons. The application of SS and its compost with straw affected the overall chemical composition of the soil (Table 1).

The form of fertilizer application is of some importance for the accumulation of chemical elements in the soil. The content of the vast majority of nutrients increased along with the dose of fresh SS, especially oxygen, phosphorus, sulfur, aluminum, calcium, manganese. For potassium and magnesium, this trend is less pronounced. For iron, the inverse dependence of its content in the soil on the increase in the rate of application of SS in different versions of the experiment was observed. Moreover, the increase in the rate of application of SS from 20 to 40 t/ha led to a decrease in iron content by 0.19%.

The use of compost with SS and straw of cereals ambiguously affected the accumulation of chemical elements in the soil. For example, the magnesium content in the variants where compost was applied remained at the highest level of 0.50–0.7%, which corresponded to the indicators of variants (4–6) with the addition of SS. In the variant with the application of 20 t/ha of compost (option 7), the manganese content was almost at the level of the option, where only mineral fertilizers were applied (option 3), and the application of 30 t/ha (option 8) was one of the highest contents of this element. A similar trend was observed for the aluminum content. For sulfur, potassium, calcium, the values in these variants (options 7 and 8) were at the average level.

Changes in the content of mineral nutrients in plants occurred at different rates of SS**.** The application of fertilizers affected not only the accumulation of nutrients in the soil, but also caused changes in the chemical composition of plants (Table 2 and Table 3).

The content of the most of the chemical elements in *Helianthus tuberosus* tubers have grown under the influence of increasing the dose of SS. In particular, the oxygen content increased significantly to 47.3–48.4% in the variants with the highest doses (variants 5 and 6). However, in variants 7 and 8, where composts with SS and straw and compensatory doses of mineral fertilizers were

Table 1. The content of individual elements in the layer of 0–30 cm of soil for the introduction of SS and its composts with straw cereals, % (average for 2017–2020)

Chemical element	Before starting the experiment	Experience options							
		1	2	3	4	5	6	7	8
O	47.44±0.01	48.02±0.02	48.33±0.02	49.68±0.03	48.76±0.02	49.08±0.03	50.08±0.05	50.01±0.05	50.66±0.06
Mg	0.44±0.03	0.45±0.04	0.53±0.05	0.58±0.05	0.51±0.05	0.60±0.8	0.63±0.05	0.50±0.05	0.68±0.07
Al	3.11±0.06	3.54±0.02	4.05±0.03	4.98±0.05	4.02±0.04	4.81±0.05	4.88±0.05	3.81±0.03	4.67±0.04
Si	38.20±0.02	36.10±0.03	36.20±0.04	36.75±0.03	37.14±0.05	37.55±0.06	37.62±0.06	36.22±0.05	36.99±0.05
P	0.10±0.004	0.12±0.004	0.11±0.004	0.16±0.003	0.15±0.006	0.19±0.006	0.13±0.003	0.12±0.002	0.14±0.002
S	0.15±0.002	0.16±0.03	0.17±0.01	0.20±0.02	0.23±0.01	0.26±0.2	0.29±0.02	0.20±0.03	0.25±0.03
Cl	0.08±0.001	0.11±0.002	0.09±0.001	0.09±0.001	0.08±0.002	0.09±0.002	0.11±0.003	0.09±0.002	0.09±0.002
K	2.84±0.02	3.11±0.03	2.93±0.02	3.45±0.03	3.73±0.03	3.92±0.03	3.42±0.03	3.73±0.03	3.88±0.03
Ca	0.34±0.003	0.40±0.001	0.41±0.002	0.48±0.003	0.41±0.002	0.48±0.02	0.46±0.01	0.45±0.003	0.49±0.004
Mn	0.23±0.001	0.21±0.004	0.23±0.03	0.25±0.001	0.27±0.003	0.28±0.003	0.33±0.001	0.26±0.002	0.29±0.003
Fe	0.88±0.01	1.54±0.01	1.67±0.01	1.98±0.02	1.97±0.01	1.92±0.01	1.78±0.01	1.84±0.01	1.88±0.01

Table 2. The content of chemical elements in Helianthus tuberosus for the introduction of SS and composts based on it and straw, % (average for 2017–2020)

Chemical element	Experience options							
	1	2	3	4	5	6	7	8
O	44.1±0.04	44.9±0.04	46.5±0.05	45.7±0.04	47.3±0.05	48.4±0.05	34.0±0.03	31.2±0.03
Mg	0.69±0.08	0.63±0.07	0.73±0.09	0.68±0.08	0.79±0.09	0.77±0.08	0.77±0.07	0.83±0.04
Al	5.11±0.06	4.10±0.03	4.90±0.04	4.89±0.04	4.67±0.06	4.44±0.09	4.31±0.02	4.97±0.06
Si	31.2±0.07	31.0±0.08	31.4±0.09	31.7±0.07	31.9±0.07	32.3±0.09	33.6±0.02	33.8±0.06
P	1.12±0.01	1.17±0.02	1.31±0.02	1.29±0.02	1.45±0.03	1.42±0.02	1.71±0.02	1.88±0.04
S	0.10±0.004	0.09±0.003	0.10±0.004	0.09±0.002	0.10±0.003	0.10±0.001	0.07±0.002	0.09±0.003
Cl	0.12±0.02	0.15±0.02	0.16±0.02	0.12±0.01	0.11±0.01	0.10±0.01	0.14±0.02	0.12±0.02
K	7.61±0.07	7.45±0.07	8.28±0.08	6.98±0.05	7.56±0.07	7.89±0.06	6.71±0.02	6.21±0.02
Ca	1.31±0.03	1.38±0.03	1.43±0.04	1.29±0.02	1.79±0.03	1.86±0.002	1.58±0.05	1.77±0.020
Mn	0.07±0.002	0.06±0.001	0.08±0.001	0.09±0.002	0.08±0.002	0.08±0.001	0.08±0.002	0.09±0.002
Fe	1.55±0.02	1.67±0.02	1.83±0.02	1.57±0.02	1.74±0.02	1.87±0.01	1.78±0.002	1.89±0.002

applied, the oxygen content in the tubers decreased to 31–34%, and with increasing the compost dose, the percentage of this element decreased. This phenomenon requires additional study at the level of determining the biochemical composition of tubers and oxygen-containing compounds.

The effect of fertilizers on the chemical composition of the vegetative (aboveground) mass of *Helianthus tuberosus* was also ambiguous (see Table 3).

Compared with the control without fertilizers, in all variants where fertilizers were applied, the content of chemical elements in the vegetative mass of *Helianthus tuberosus* increased. The tendencies to increase the content of chemical elements in the vegetative mass of *Helianthus tuberosus* with certain deviations are generally similar to the patterns of their accumulation in tubers. However, the accumulation of aluminum and chlorine in the vegetative mass increased along with the rate of SS and significantly exceeded the control variant– by 0.3–0.4% (for aluminum) and 1.1–2.2% (for chlorine). The use of SS in the form of composts led to even higher rates – 1.6% for aluminum and 5.6–5.8% for chlorine, compared to the introduction of fresh SS.

To assess the peculiarities of the absorption of chemical elements by *Helianthus tuberosus* plants, CBA was calculated, which reflects the ratio of the content of an individual chemical element as a percentage in the plant (vegetative mass) to its content in soil (Table 4).

The CBA for most chemical elements are more than 1, which indicates a significant accumulation of these chemical elements in plants compared to soil. High CBA are characteristic of Mn, K,

Table 3. The content of chemical elements in the vegetative mass of Jerusalem artichoke for the introduction of SS and composts based on it and straw, % (average for 2017–2020)

Chemical element	Experience options							
	1	2	3	4	5	6	7	8
O	28.29±2.7	30.42±2.9	31.61±3.2	29.84±2.8	30.55±3.0	31.84±3.1	27.56±2.84	27.92±3.1
Mg	4.14±0.02	4.75±0.03	5.23±0.05	5.72±0.04	5.90±0.06	5.95±0.04	5.12±0.05	5.71±0.05
Al	1.05±0.02	1.22±0.04	1.49±0.06	1.32±0.03	1.48±0.04	1.49±0.03	1.55±0.03	1.59±0.05
Si	3.46±0.01	3.56±0.02	4.43±0.05	4.79±0.04	4.98±0.06	5.97±0.04	5.57±0.06	5.92±0.05
P	3.40±0.03	3.55±0.04	3.89±0.05	3.66±0.05	3.99±0.05	3.75±0.05	4.23±0.06	4.69±0.06
S	0.88±0.001	0.89±0.002	0.90±0.002	0.92±0.001	0.93±0.004	0.94±0.003	0.88±0.004	0.92±0.005
Cl	0.39±0.004	0.51±0.005	0.58±0.006	0.46±0.004	0.57±0.006	0.59±0.005	0.56±0.006	0.58±0.007
K	27.69±0.29	28.11±0.28	30.91±0.32	29.23±0.29	30.22±0.31	31.5±0.33	33.21±0.31	34.54±0.36
Ca	20.26±0.41	20.45±0.39	24.33±0.35	20.72±0.24	24.80±0.29	24.92±0.26	24.66±0.29	24.72±0.31
Mn	0.33±0.001	0.34±0.001	0.39±0.002	0.47±0.001	0.57±0.001	0.68±0.001	0.42±0.002	0.46±0.002
Fe	0.18±0.002	0.20±0.001	0.26±0.002	0.30±0.002	0.370±0.001	0.42±0.001	0.33±0.003	0.28±0.001

Mg, P, Ca, S. The highest indicators of biological absorption of Jerusalem artichoke are calculated for calcium, which in the experimental conditions are 43.4–59.0. However, depending on the change in the nutritional conditions of the crop, this indicator varied relatively insignificantly up to 10%. Indicators of biological absorption coefficients Al, Si, Cl, Fe are low values, lesser than 1.

According to the results of correlation-regression analysis of P and K (Fig. 1), Ca and Mg (Fig. 2), it

Table 4. Indicators of CBA of chemical elements with Jerusalem artichoke (*Helianthus tuberosus*), depending on the introduction of SS, the average for 2017–2010

Chemical element	Experience options							
	1	2	3	4	5	6	7	8
O	0.59	0.63	0.64	0.61	0.62	0.64	0.59	0.61
Mg	9.20	8.96	9.02	11.22	9.83	9.44	10.24	8.40
Al	0.30	0.30	0.30	0.33	0.31	0.31	0.41	0.34
Si	0.10	0.10	0.12	0.13	0.15	0.15	0.14	0.15
P	28.32	32.27	23.72	24.40	20.53	26.22	35.25	33.50
S	3.01	3.82	4.50	4.00	3.58	3.24	4.40	3.68
Cl	3.55	5.67	6.44	5.75	6.33	5.36	6.22	6.44
K	8.90	9.59	8.96	7.84	7.71	9.24	8.91	8.91
Ca	50.65	49.86	59.01	50.51	43.38	51.67	54.81	50.45
Mn	1.57	1.49	1.56	1.74	2.04	2.06	1.62	1.59
Fe	0.12	0.12	0.13	0.15	0.19	0.24	0.18	0.15

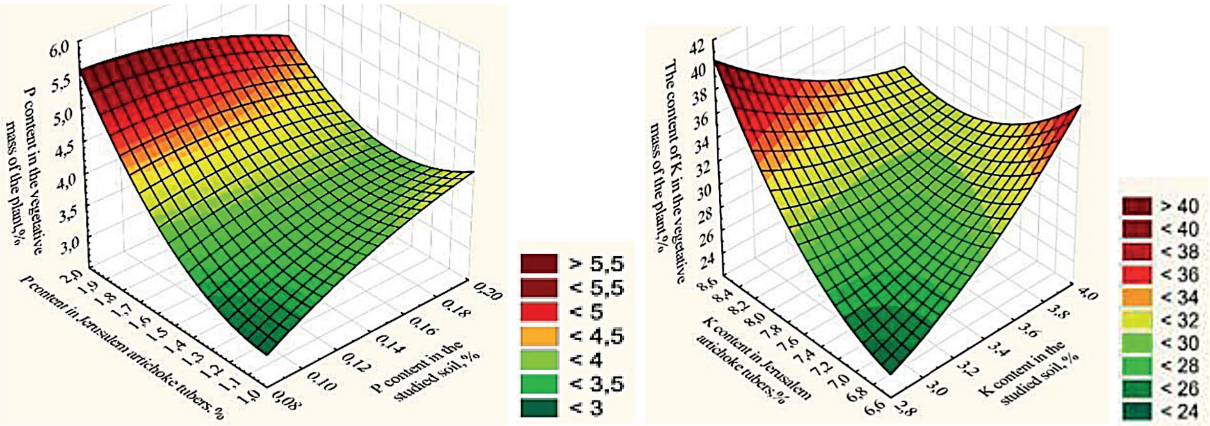

Figure 1. Models of dependence of the content of elements P (a) and K (b) in the vegetative mass of *Helianthus tuberosus* on their content in Jerusalem artichoke tubers and the studied soil, %

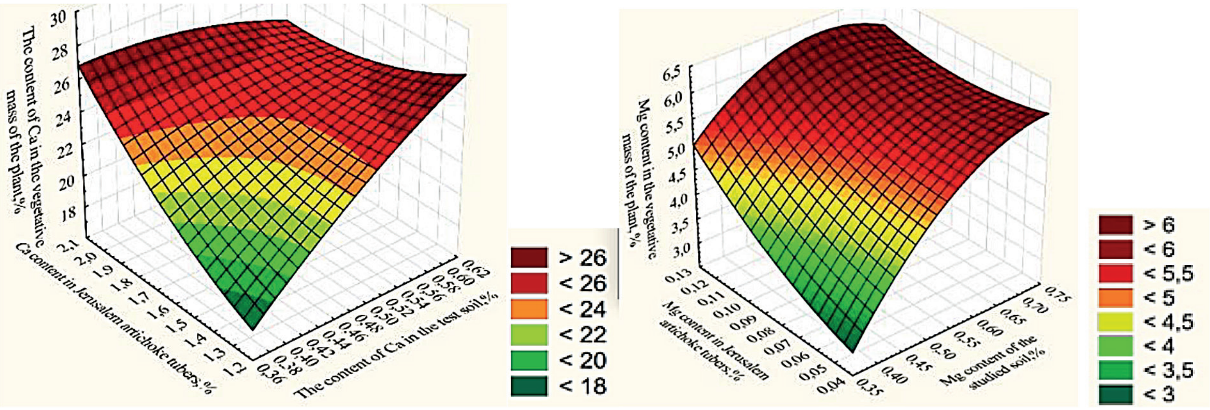

Figure 2. Models of dependence of the content of elements Ca (a) and Mg (b) in the vegetative mass of Helianthus tuberosus on their content in Jerusalem artichoke tubers and the studied soil, %

Table 5. Calculation models of dependence of the content of individual elements in the vegetative mass of *Helianthus tuberosus* on their content in soil and tubers

Element	Regression equation	r	R^2
P	$z = 2.4228 + 40.1714x - 3.4384y - 46.3858x^2 -17.0391xy + 2.4613y^2$	0.86	0.73
K	$z = -7.5143 + 44.1061x - 13.8008y + 4.0135x^2 - 9.1287xy + 3.11293y^2$	0.72	0.67
Ca	$z = -27.0267 + 138.4833*x+13.2925*y - 41.5843*x^2 - 51.0528*x*y + 4.545*y^2$	0.82	0.75
Mg	$z = -5.197 + 29.3878x + 22.6373y - 17.927x^2 - 57.2845xy + 117.3134y^2$	0.71	0.63

Note: *z* – the content of the element in the green mass of *Helianthus tuberosus*, %; x – content of the element in the studied soil, %; *y* – element content in *Helianthus tuberosus*, %.

was determined that their content in the vegetative mass of Jerusalem artichoke significantly depends on the content in Jerusalem artichoke tubers and soil.

Models of the dependence of the content of these nutrients in the vegetative mass of Jerusalem artichoke can be described by the following quadratic regression equations (Table 5).

The high closeness of the relationship between the content of the element in the green mass and in the soil and tubers for phosphorus and magnesium as well as moderate for potassium and calcium is confirmed by the values of the coefficients of multiple determinations.

In the course of research, the ambiguous influence of SS on the content of elements in the soil, their assimilation, accumulation and redistribution in underground (tubers) and aboveground (vegetative mass) organs of *Helianthus tuberosus* was established.

CONCLUSIONS

Therefore, the use of SS as a fertilizer for Jerusalem artichoke (*Helianthus tuberosus*) has a significant effect on changing the chemical composition of Eutric Podzoluvisols, increasing the total content of most elements. However, this impact is not unambiguous and varies considerably depending on the form of SS. The highest rate of 40 t/ha of fresh SS with the corresponding amount of mineral fertilizers in terms of $N_{90}P_{90}K_{90}$ provides under the experimental conditions the highest content of Al – 4.9%, Si – 3.8, Mn – 0.33, S – 0.29%. Application of equivalent in terms of nutrient content of SS – (30 t/ha) in the form of compost with cereal straw (3:1) and compensatory dose of mineral fertilizers provides the highest soil content O – 30.1%, K – 3.9, Fe – 1.9, Mg – 0.7, Ca – 0.5%.

Changing the conditions of mineral nutrition of *Helianthus tuberosus* causes significant changes in the chemical composition of its tubers and vegetative mass. Studies have shown a clear positive effect of increasing rates of fresh SS on the increase in the content of tubers: O – up to 48%, K – up to 7.9, Ca – up to 1.9, Fe – up to 1.9, in green mass: O – up to 31.8%, K – up to 31.6, Ca – up to 24.9, Mg – up to 5.9, Mn – up to 0.7, Fe – up to 0.4%. The use of SS in the form of compost with cereal straw and compensatory dose of mineral fertilizers for the content of basic macronutrients (NPK) provides the highest content of P – 4.7 and K – 34.5%.

The CBA calculated on the basis of experimental studies for the vast majority of elements are more than 1, which indicates a high intensity of accumulation of individual elements in *Helianthus tuberosus* plants, compared to their concentration in soil. Thus, for Ca the coefficient of biological absorption is 43.4 – 54.8, P – 20.5 - 35.2, Mg – 8.4 - 11.2, K – 7.7 - 9.6. For O, Al, Si, Fe, the biological absorption coefficients were less than 1.

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