Measurement of transfer factor – TF of radioactive elements in the fast-growing plant culture Helianthus tuberosus L (sunchoke)

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Highlights

- In this paper it is determined the specific activities of radionuclides K-40, Ra-226, Cs-137 and Th-232 in soil and different parts of the plant Helianthus tuberosus L. (sunchoke)
- Measurements were performed by the gammaspectrometry method using a high-resolution HPGE detector.
- Based on the obtained results, transfer factors (TF) were calculated for individual radionuclides between soil and individual parts of sunchoke plant.
- Differences in the accumulation of radionuclides in the tubers stem and aerial parts of the plant were analyzed.
- The obtained TF values were compared with data from relevant scientific works and published data.

Abstract

Research of usage of biomass for energy purposes is an important topic for the sustainable development and application of renewable energy sources in areas with developed agricultural production. As the basis for using renewable energy sources in technology, it is planned to grow fast-growing crops that have a high biomass yield per hectare. The use of renewable energy sources can be achieved by obtaining a large amount of organic matter for the production of biogas, which is then used in the cogeneration process [1] for the production of heat and electricity. A fast-growing crop, the plant Helianthus tuberosus L. - sunchoke, is an example of a crop that can be used for high biomass yield, as it grows with a yield of 130 to about 150 tons per hectare per year [2]. Thus, obtaining a significant amount of biomass where the carbon in the biomass structure is completely created from CO_2 from the atmosphere.

Sunchoke accumulates significant amounts of nutrients, including radionuclides from the soil. After biogas production, biomass is separated into liquid fertilizer and solid residue, in which radionuclides remain. Since both products return to the soil and potentially re-enter the food chain, it is necessary to evaluate the factors of radionuclide transfer from the soil to individual parts of this cultivated industrial plant.

The research included sampling on two plots in Vojvodina. Several sunchoke plants were sampled in the post-flowering period, along with the soil in which the crop was grown. After sampling, the plants were separated into tubers, stems, leaves and flowers, and the radionuclide content was measured using an ORTEC HPGe GMX detector system [3] with the basic setting in the Laboratory of the Department of Nuclear Physics. The measured activity concentrations of detected radionuclides were in the following ranges: Cs-137, 2.84–12.5Bq/kg in soil and 0.6–1.67Bq/kg in tubers; Ra-226, 21.7–37.3Bq/kg in soil and 4.8–17.9Bq/kg in stems; and K-40, 399–553Bq/kg in soil and 705–1330 Bq/kg in flowers and leaves

Based on the ratio of measured activity concentrations, radionuclide transfer factors for all samples were calculated according to the IAEA TRS-472 methodology [4]. The most important result of this research is that the plant reconcentrates potassium (K-40) in all its parts, which can affect the safety of food production and the exposure of the population through nutrition

1. Introduction

With the implementation of fast-growing energy crops, such as Helianthus tuberosus L. or popularly called - "sunchoke", it is possible to capture a significant amount of CO_2 from the atmosphere using solar energy in the process of photosynthesis. The importance of this plant is that it can create significant amounts of biomass, if intensive irrigation is carried out and organic fertilization of the soil on which it grows. The application of adequate measures enables the yield of sunchoke up to 150 t/ha of green biomass [2], whereby one ton of biomass binds about 2.2t of CO_2 from the atmosphere, i.e. a total of approximately 396t of CO_2 per hectare.

The biomass generated by sunchoke has a high moisture content and is loose, therefore it is necessary to use sunchoke biomass in anaerobic digestion in biogas plants, which produces methane. The yield of biogas production from sunchoke, namely Helianthus tuberosus L. - a French variety, was measured experimentally in the Czech Republic in 2014 [5] and the plant was cultivated in Serbia in the municipality of Inđija. The experiment estimated the values of biogas yield that one ton of OS (organic solids) produces 585m3 of biogas, which is about 3500kWh of heat energy [6] only from the green sunchoke biomass. Also data on biogas yield from green sunchoke biomass from Sardinia mention measurements that are below the average or about $325 \pm 66m^3$ per one ton of OS [7] , but these measurements were characterized as being below average due to the decrease in soil moisture in which sunchoke was grown

Sunchoke is a perennial plant, with a development period of up to 20 years on some surface, as a result of which there is an accumulation of radioactive elements from the soil in the structure of the plant. Radioactive elements are returned to the soil on which sunchoke grows through organic fertilization of products from biogas production. If the organic biomass of the solid phase is not returned to the surface where sunchoke grows, then the amount of radioactive elements in the soil is reduced, which is called remediation of contaminated soil.

It can be concluded that sunchoke is a plant that uses the mineral composition of the soil very efficiently, partially weakening the quality of the soil, as generations of new plants are inherited. Therefore, it is imperative that the appropriate mineral composition is returned to the soil, which can be achieved with organic soil fertilization from digestion products.

For the above reasons, it is necessary to analyze the concentration of radioactive elements using gamma spectrometry in the soil as well as in all parts of the plant, separately for the tubers, stem, leaf and flower in order to determine the values of the transfer factor (TF) and the functional dependence between the concentrations in certain parts of the plant. With the obtained functions, it is possible to approximately calculate the concentrations of radioactive elements that can be expected in certain parts of plants that are similar to sunchoke, depending on the concentration of radioactive elements in the soil.

2. Transfer factors of radioactive elements in plants

Transfer factors of radioactive elements in plants represent the ratio between the concentration of a certain radioactive element in the plant mass and the concentration of that element in the soil in which the plant grows. This factor is used to estimate how plants accumulate radioactive isotopes from the soil [8] which can be significant for the assessment of soil pollution and potential exposure of plants to radioactive substances. The formula for transfer factor (TF) is usually:

$$TF = \frac{C_{plant}}{C_{soil}} \tag{1}$$

C_{plant} - the concentration of the radioactive element in the plant mass, with the unit $\frac{Bq}{kg}$

C_{soil} - the concentration of the same element in the soil, with a unit $\frac{Bq}{kg}$

Transfer factors can vary significantly between different plant species and different radioactive elements. Factors that affect these values include soil type, plant type, soil pH, amount of organic material in the soil, and other environmental conditions.

3. Sampling

Two series of sunchoke samples were taken from plot owners who have sunchoke Helianthus tuberosus L French variety on agricultural land, which did not have irrigation and fertilization measures. The first group of samples was taken in the village of Pivnice, in a garden whose soil is characterized by an increased degree of humidity and a higher percentage of clay at the surface. There is no information about any pollution in that area. Date of sampling was October 14, 2024. In this field, sunchoke grows in groups and is not planted in plantations. The first sampled plant that did not have a flower was a 5-year-old plant. Another plant was sampled at 3 years of age and this plant had a flower. The third sampled plant is also 3 years old, but it did not have a flower.

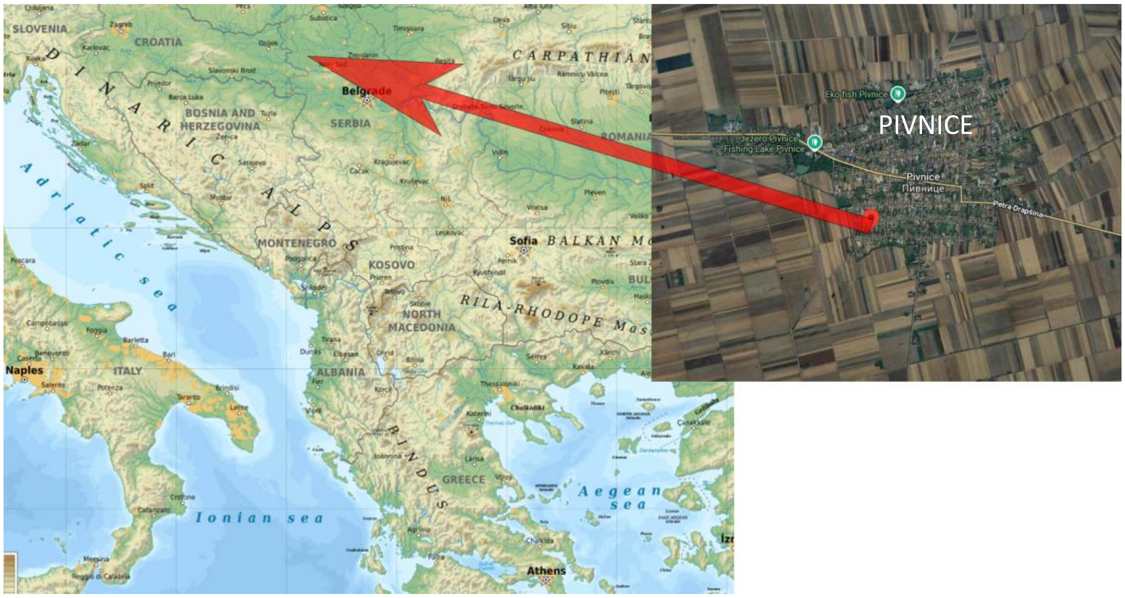

Figure (1) The first sampling location in the village of Pivnice northwest of Novi Sad

The second group of samples was taken in the fields of the village of Omoljica, whose land is close to the Pancevo oil refinery at a distance of about 13 km. Sampling was carried out on October 20, 2024. Plants were 6 years old, growing in larger groups. All plants had clearly defined flowers and were also not plantation grown plants. Plant growth conditions in Omoljica due to watering are better than in Pivnice, so plant rhizomes are larger and numerous plants have flowers.

Figure (2) Second sampling location in the village of Omoljica southeast of Pancevo,

For each plant, samples were divided into: soil sample, tuber (rhizome), stem, leaf and flower. The tubers were specially washed and cleaned, with the removal of excess roots and soil. The stems and leaves are cut into smaller pieces. After this preparation, samples were dried in an oven at 105 degrees Celsius to a constant mass of the material. After drying, the samples were crushed and packed in plastic containers with a diameter of 70 mm and an appropriate height depending on the amount of the sample. After packaging, the samples were left in plastic containers for 30 days to reach radon equilibrium.

4. Detection system

The detector system that was used to measure radioactivity was manufactured by ORTEC, type GMx-HPGe with a beryllium window. The efficiency of the detector is 32%. The detector is placed in "home-made" lead shielding with a wall thickness of 12 cm Pb and layers of 1 mm Cu and 1 mm Sn. The accompanying electronics are also manufactured by ORTEC. The collection and processing of the spectra is done with the software program GENIE-2000. More details about detector system can be seen in the paper [3]. Detector calibration was performed using a standard multiple radionuclides source to cover the entire energy spectrum [9] and with IAEA reference materials such as "Moss Soil" [10] and „Irish Sea Sediment" [11] IAEA materials with PT schemes that the laboratory owns were also used. The ANGLE software was used to transfer the required geometry from the standard to the sample [12], with more information about ANGLE software [13] .

5. Measurement results

Table (1) Distribution of measured values of concentration of radioactive elements for samples with measurement uncertainties

Sample code	Element	Soil activity [Bq/kg]	Tuber activity [Bq/kg]	Stem activity [Bq/kg]	Leaf activity [Bq/kg]	Flower activity [Bq/kg]
Sample I 2. - 3 god.	Ra-226	37.3±1.2	7.5±0.9	12.5±1.1	10±3	48±43
	Th-232	36.3±2	3±0.6	2.4±0.8	9±2	72±24
	K-40	518±13	872±43	476±27	713±41	1330±300
	Cs-137	< MDA	< MDA	< MDA	< MDA	< MDA
Sample I 3. - 3 god	Ra-226	34.9±1.2	47±4	4.8±0.9	9.9±2.3	/
	Th-232	36.8±1.9	9.8±1.8	3.7±0.6	3.3±0.8	/
	K-40	553±13	1160±63	560±50	849±49	/
	Cs-137	3.1±0.2	< MDA	< MDA	< MDA	/
Sample I 1. – 5 god	Ra-226	37.2±1.3	10±1.1	17.9±1.9	6±2	/
	Th-232	37.1±1.3	4.4±1.2	8.9±1.5	5±2	/
	K-40	528±13	851±44	685±39	1130±110	/
	Cs-137	3.77±0.24	0.63±0.34	1.84±0.86	< MDA	/
Sample II 1. - 6 god.	Ra-226	24±1	2.3±0.8	5.1±1.9	2.1±1.8	12±8
	Th-232	24.1±0.9	1.8±0.6	3.1±1.8	3.1±1.3	24±7
	K-40	423±11	674±18	73±15	209±19	1120±73

	Cs-137	8.5±0.4	0.6±0.3	< MDA	< MDA	< MDA
Sample II 2. - 6 god	Ra-226	21.7±0.9	3.9±0.7	2±2	10±2	16±7
	Th-232	21.2±0.8	9.1±1	1.4±0.9	4.7±0.8	22±7
	K-40	399±10	523±19	128±13	219±22	705±53
	Cs-137	12.5±0.4	1.67±0.56	< MDA	< MDA	< MDA

Note: Where / stand is that there were no flower in that plant sample, which is the case with two plants in Pivnice. <MDA - minimum detectable activity represents the lowest radionuclide activity that can be reliably registered above the background radiation level with a predefined statistical certainty [4].

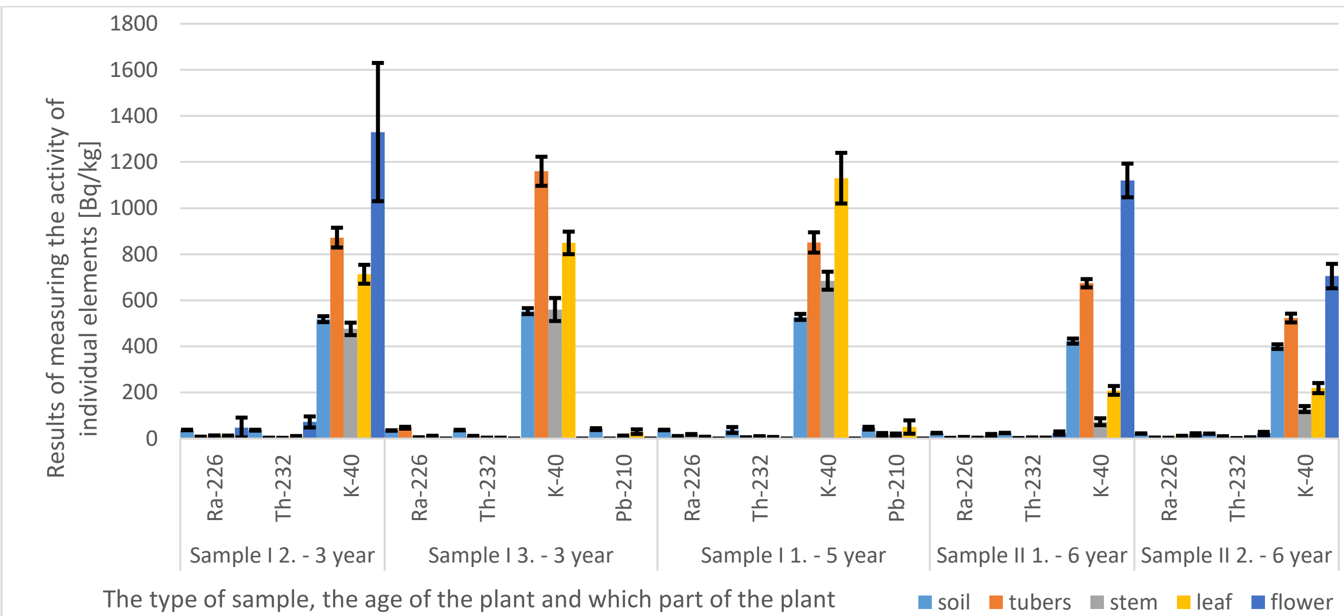

Figure (3) Presentation of the activity concentration of individual radioactive elements with measurement uncertainties in relation to the samples, the age of the plant and the parts of the plants that were used in the measurement

According to relation (1) through the ratio of the concentrations of radioactive elements of individual parts of the plant with the comparison of the concentration of the same elements from the soil, the transfer factors - TF for all parts of the plant can be calculated with the calculation of measurement uncertainties.

Table (2) Presentation of the values of the concentration of the activity of certain radioactive elements from the soil in relation to the calculated value of the transfer factor (TF) for each part of the plant

Element	Sample code	Soil activity [Bq/kg]	TF –tuber	TF – stem	TF – leaf	TF - flower
K-40	I 1.1	528±13	1.61±0.09	1.3±0.08	2.14±0.21	/
K-40	I 2.1	518±13	1.68±0.09	0.92±0.06	1.38±0.09	2.57±0.58

K-40	I 3.1	553±13	2.1±0.12	1.01±0.09	1.54±0.1	/
K-40	II 1.1	423±11	1.59±0.06	0.17±0.04	0.49±0.05	2.64±0.18
K-40	II 2.1	399±10	1.31±0.06	0.32±0.03	0.55±0.06	1.77±0.14
Cs-137	I 1.1	3.77±0.24	0.17±0.09	0.49±0.23	N/A	/
Cs-137	I 2.1	2.84±0.28	N/A	N/A	N/A	N/A
Cs-137	I 3.1	3.1±0.2	N/A	N/A	N/A	/
Cs-137	II 1.1	8.5±0.4	0.07±0.04	N/A	N/A	N/A
Cs-137	II 2.1	12.5±0.4	0.13±0.04	N/A	N/A	N/A
Ra-226	I 1.1	37.2±1.3	0.27±0.03	0.48±0.05	0.16±0.05	/
Ra-226	I 2.1	37.3±1.2	0.2±0.02	0.34±0.03	0.27±0.08	1.29±1.15
Ra-226	I 3.1	34.9±1.2	1.36±0.12	0.13±0.02	0.28±0.06	/
Ra-226	II 1.1	24±1	0.1±0.04	0.21±0.08	0.09±0.08	0.5±0.33
Ra-226	II 2.1	21.7±0.9	0.18±0.03	0.09±0.09	0.46±0.09	0.74±0.32
Th-232	I 1.1	37.1±1.3	0.12±0.03	0.24±0.04	0.13±0.05	/
Th-232	I 2.1	36.3±1.9	0.08±0.02	0.67±0.02	0.25±0.06	1.98±0.67
Th-232	I 3.1	36.8±1.3	0.27±0.05	0.1±0.02	0.09±0.02	/
Th-232	II 1.1	24.1±0.9	0.07±0.02	0.13±0.08	0.13±0.05	0.99±0.3
Th-232	II 2.1	21.2±0.8	0.43±0.05	0.07±0.04	0.22±0.04	1.04±0.1

Note: **TF - tuber** was calculated by dividing the element activity concentration measured in the tuber to the activity concentration in the soil. **TF - stem** is calculated by dividing the concentration of the activity of the element measured in the stem to the concentration of the element in the soil. **TF - leaf** was calculated by dividing the element activity concentration measured in the leaf by the element concentration in the soil samples. **TF - flower** was calculated by dividing the concentration of the activity of the element measured in the flower to the concentration of the element measured in the soil. **N/A -** The presence of the radioactive element was not detected, therefore, the TF for the given ratio was not calculated.

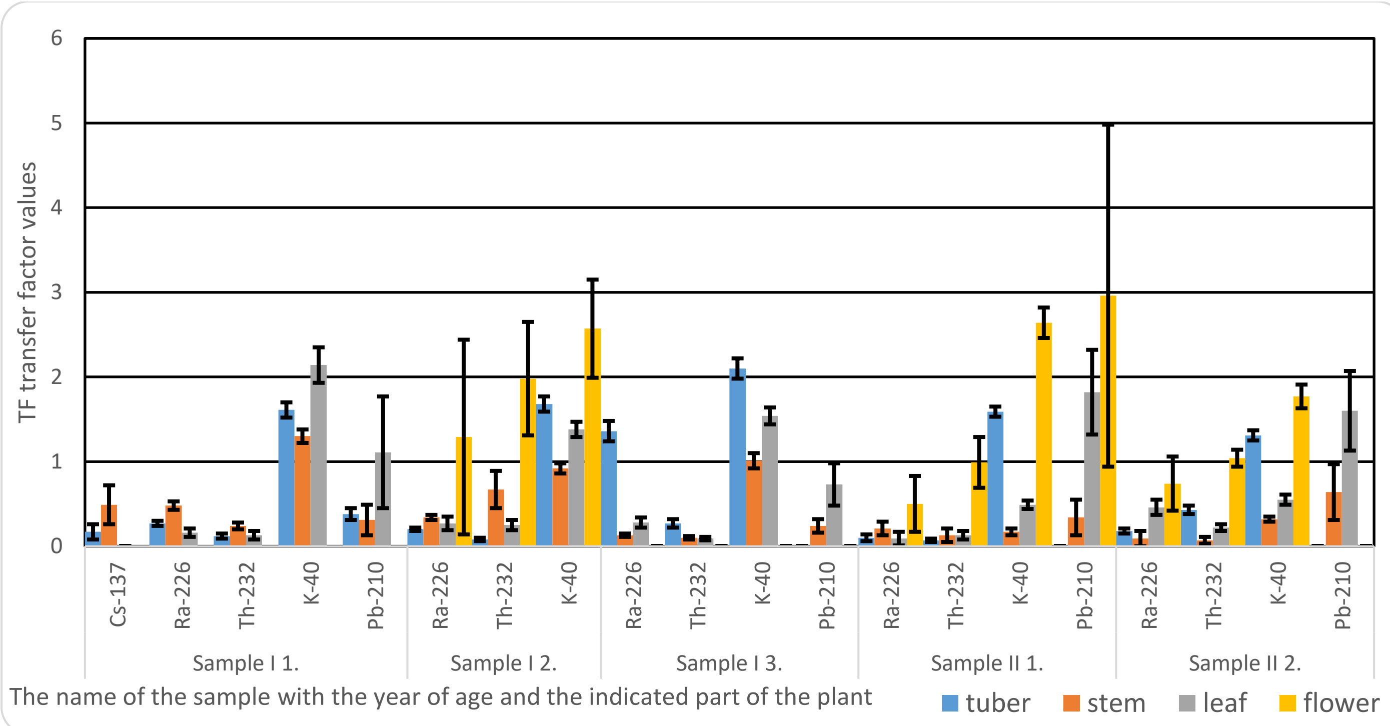

Figure (4) Presentation of transfer factor (TF) values with measurement uncertainties from Table 2 depending on the sample series, information on the age of the plant and the indicated part of the plant used in the measurement

Table (3) Presentation of the ratio of Transfer Factor results for K-40 and Cs-137 with the table values listed in the collection from literature in relation to the calculated TF obtained in the experiment

Part of plant	TF - tuber	TF - stem	TF - leaves	TF - flower
K40 from table value [4]	1.3	1.1	1.3	1.3
TF Mean value of K- 40	1.66±0.08	0.74±0.06	1.22±0.10	2.3±0.3
Relative Deviation for K-40	**24%**	**38%**	**6%**	**56%**
Cs-137 from table value [4]	58.10^{-2}	58.10^{-2}	/	/
TF Mean value of Cs-137	0.12±0.06	0.49±0.23	N/A	N/A
Relative Deviation for Cs-137	**21%**	**84%**	N/A	N/A

Note: TF from the collection table are taken for sunflower as plant is similar to sunchoke; from table value – meaning values of TF are taken from previous measurements from reference [4].

Cs-137 was detected only in the tubers and in the stems. In other parts of the plants it was below the MDA [14] (<MDA - minimum detectable activity represents the smallest radionuclide activity that can be reliably registered above the level of background radiation with predefined statistical certainty), and therefore only TF for tuber-soil is compared). The similarity of transfer factors between sunflower and sunchoke can be explained by their taxonomic affinity, similar physiology of element adoption, developed root system and comparable mechanisms of

translocation of radionuclides inside the plant. TF values are slightly higher for sunchoke because it has a slightly higher affinity for radionuclides.

The highest values of activity concentration in sunchoke were obtained for Potassium K-40. There is little data regading TF values for K-40 from known table values [4], but the mean values of TF are taken for vegetables and for plants intended for silage. With the mentioned values, the experimental measurement gave good matching results in relation to the previously set measurements that were systematized. It can be concluded that the matching of results, occurred as a consequence of the higher concentration of Potassium K-40 in sunchoke. As it can be seen from the data, accumulation occurs in the leaves also. This factor is important, because K-40 is transferred to the next generation of sunchoke plants due to the return of organic fertilizer after the biogas production process. Taking into consideration age of plants there is no increase in the concentration of radionuclides with the age of the plant, but rather the concentration of K-40 in the plant is relatively constant from the beginning of growth and remains the same regardless of the age of the plant.

6. Analysis of obtained values - functional dependence of TF

One of the possibilities for examining the functional dependence from relation (1) is to establish a linear dependence (linear fit) between the concentrations of radionuclides from the soil for individual elements in relation to the values of the TF - transfer factor, where the measurement uncertainties are also included in the analysis

$$C_{plant} = k \cdot C_{soil} \tag{2}$$

where k - is a direct relationship between the measured value and the concentration of radionuclides from the soil. The assumption is that this type of dependence is possible if conditions are: low to moderate concentrations, when there is no saturation of the root-tuber system and when the chemical forms of radionuclides remain available for measurement. In order to examine the validity of the measurements, data analysis should be performed comparing the value of the concentration of radioactive elements from the soil for individual elements and samples, as a dependent component of the function and TF as an independent variable.
Another type of functional dependence that can be analyzed is non-linear fit:

$$TF = f(\mathrm{C}_{soil}^{-b}) \quad \text{or a dependency can be written } y = a \cdot x^{-b} \tag{3}$$

The data related to the x-axis is the concentration of radioactive individual elements, and the value of the transfer factor represents dependent parameters and belongs to the y-axis. Origin 2018 is the program where the analysis was performed, where first the analysis was performed for the non-linear function and then the analysis for the linear function. For all established relations, the method of least squares for linear junction gives a better mathing between the concentration ratio between the soil and other parts of the plant, as well as the analysis between the concentrations of radioactive elements in the soil in relation to the transfer factors of specific part of plant.

All analyzes are available in the appendix to this document, where according to the e-mail request in this paper, readers can request that the authors send them an additional document with all analyses. We give an example of the analysis of the functional dependence of TF in relation to the concentration of radionuclides in the soil for K-40, as the most present radionuclide. Determination of the dependence graph of TF for the tuber in relation to the specific activity of K-40 in the soil for non-linear fitting - $y = a \cdot x^b$

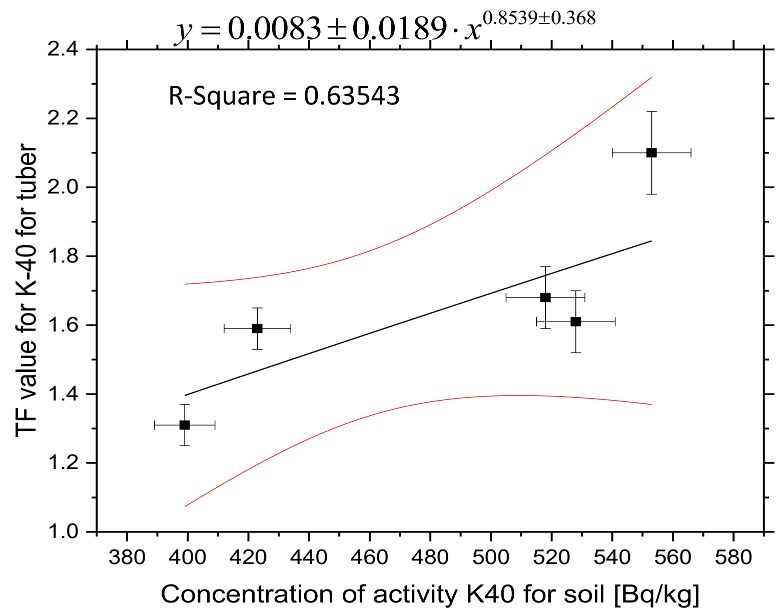

Figure (5) Dependence of the TF value for K40 for the tuber in relation to the concentration of K-40 activity in the soil - non-linear fit, Note the obtained function is written within this figure

For linear fitting to the shape of the function $y = a + b \cdot x$

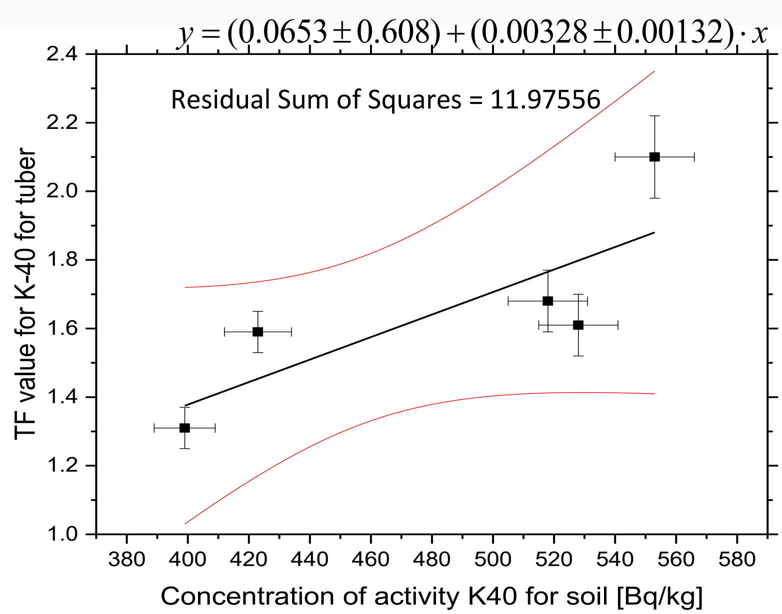

Figure (6) Dependence of the TF value for K40 for the tuber in relation to the concentration of K-40 activity in the soil - linear fit Note the obtained function is written within this figure

It is also possible to perform an analysis of the function of the K-40 concentration in the tuber in relation to the K-40 concentration from the soil, for non-linear fitting. - $y = a \cdot x^b$

$$y = (0.01016 \pm 0.0234) \cdot x^{1.82406 \pm 0.37666}$$

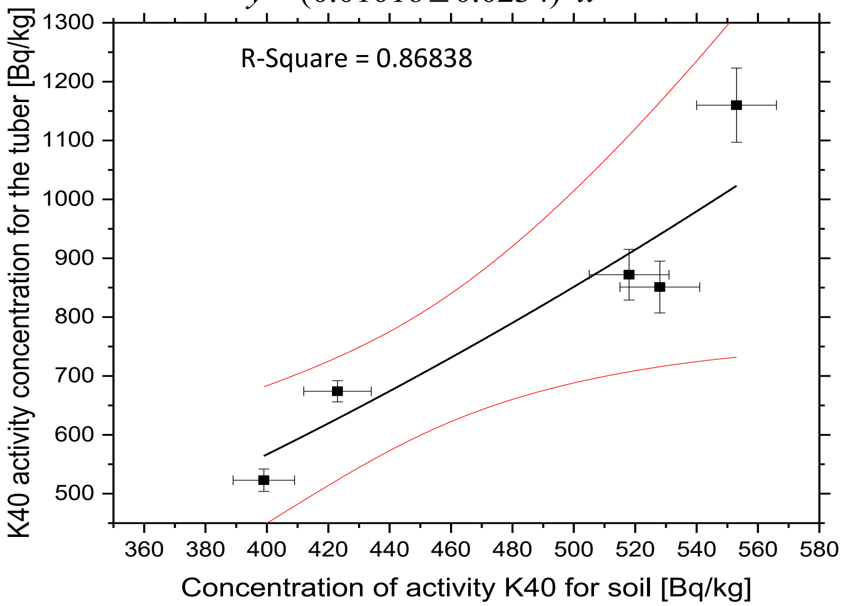

Figure (7) Dependence of the concentration of K40 activity for the tuber in relation to the concentration of K40 activity in the soil - non-linear fit. Note, the function obtained by nonlinear fitting is written within this figure

Linear fitting for the shape function $y = a + b \cdot x$

$$y = (-627.14733 \pm 282.74836) + (2.97337 \pm 0.64917) \cdot x$$

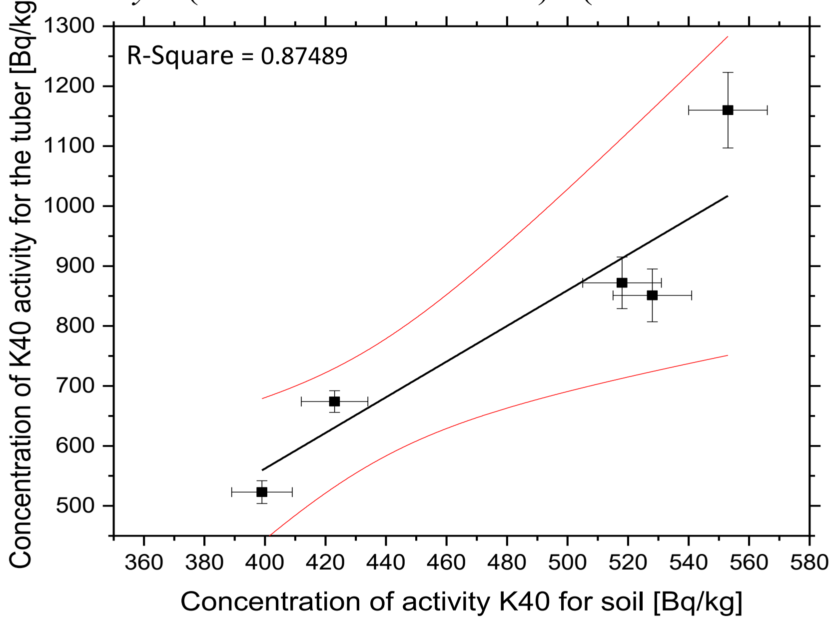

Figure (8) Dependence of the concentration of K40 activity for the tuber in relation to the concentration of K40 activity in the soil - linear fit. Note: the resulting function is written within this figure

If figures 5 and 6 are compared, as well as in the case of figures 7 and 8, a there is a better matching of the data with the obtained function and error corridor in the case of the linear function compared to the analysis performed for the non-linear function. According to the established model of the ratio of TF to the concentration of a certain radionuclide from the soil, or by analyzing the direct dependence of the concentration of radionuclide from the soil in relation to the concentration of that radionuclide in a particular part of the plant. Some results of the analysis of the function are listed in this paper, and all figures and data analysis can be viewed by contacting the authors.

Table (4) Shown linear functional dependences for TF in different parts of the plant for K-40 in relation to the specific activity of K-40 in the soil

K40		TF –tuber		TF – stem		TF – leaf		TF - flower	
Special activity		Value	Error	Value	Error	Value	Error	Value	Error
soil	a	0.0653	0.60815	-2.63438	0.78103	-3.01189	0.9164	-3.25196	4.70719
	b	0.00328	0.00132	0.00701	0.00168	0.00859	0.00199	0.01302	0.0113

Table (5) Shown linear functional dependencies for the concentration of K40 activity in different parts of the plant in relation to the specific activity of K40 from the soil and parts of the plant that transmit the radioactive elements

K40		tuber		stem		leaf		flower	
		Value	Error	Value	Error	Value	Error	Value	Error
soil	a	-627.14733	282.74836	-1301.874	383.1526	-1674.79	370.420	-2760.254	2524.426
	b	2.97337	0.64917	3.45321	0.88253	4.59014	0.8468	8.8355	6.15787
tuber	a	/	/	-386.512	300.0612	-457.5408	295.647	-380.9306	552.2019
	b	/	/	0.88484	0.44969	1.14828	0.42306	1.29592	0.57104
stem	a	/	/	/	/	83.81868	26.95645	2942.034	91.049
	b	/	/	/	/	1.35185	0.11052	-3.26396	0.1419

8. Conclusion

The obtained results indicate a clear connection between the concentration of radionuclides in the soil and their accumulation in specific part of plant, where the intensity of transfer depends on the chemical characteristics of the radionuclides, the physiological properties of the plant, as well as on the biochemical processes that regulate the uptake and transport of elements. Research results show that K-40, as a natural radionuclide and an essential element in plant metabolism, has higher transfer factor values compared to Cs-137.

This result is in accordance with generally accepted radioecological principles, according to which plants actively absorb potassium from the soil due to its key role in physiological processes such as the regulation of osmotic pressure, enzyme activation and the process of photosynthesis. Therefore, K-40 is relatively efficiently transported from the roots and tubers to the aerial parts of the plant. In contrast, Cs-137, as an anthropogenic radionuclide created mainly as a product of nuclear fission, has no biological function in plant metabolism. Although, due to its chemical similarity with potassium, it can use the same transport mechanisms in the plant, its uptake is generally more limited, which is reflected in the lower values of the transfer factor. In addition, the mobility of Cs-137 in soil is highly dependent on soil physicochemical properties,

such as clay content, organic matter, and cation exchange capacity, which can significantly affect its bioavailability [15].
Analysis of the distribution of radionuclides in certain parts of sunchoke shows that K-40 accumulates to a greater extent in the above-ground parts of the plant [16], especially in the leaves and stem, which is associated with intense metabolic activities in those parts of plant. On the other hand, Cs-137 shows a more pronounced tendency to remain in the roots and underground parts of the plant, including the sunchoke tuber. This distribution may be a consequence of limited transport of this radionuclide through xylem and phloem, as well as interactions with components of the cell wall and the soil complex [17]. From the experiment of the amount of biogas yield, it can be concluded that for the normal use of a biogas plant with a power of 1MWel, about 7100t (solid organic matter)/year of sunchoke is needed [18].
According to the measurement values from the experiment, it was obtained that the average value of the specific activity of radioactive elements for stems, leaves and flowers, i.e. parts of the plant that are removed for biogas production, was about 500Bq/kg
In the process of using organic fertilizer in the soil for a model biogas power plant of 1MWel power, about $3.6 \cdot 10^9$Bq of radioactive elements from sunchoke are returned to the soil. Most of the radioactivity comes from K-40. The stated amount of biomass can produce approximately $4 \cdot 10^6 m^3$ of biogas, which allows this amount of biogas to power a 1MWel biogas plant, and in the specified amount of biogas it can be equvalent of about 8850 tons of CO_2 from the atmosphere that have been absorbed through the biomass, which contributes to the reduction of CO_2

Credit authorship contribution statement

Aleksandar Radukin: Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation. **Jan Hansman** Writing – original draft, Supervision, Visualization, Software, Investigation, Formal analysis, Data curation. **Danijel Velimirović:** Validation, Formal analysis. **Jovana Knežević-Radić:** Conceptualization. **Dušan Mrđa:** Methodology, Investigation. **Kristina Bikit:** Validation, Conceptualization. **Sofija Forkapić:** Supervision, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability:
All data and analysis regarding this paper will be made available on request to the authors.

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