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Effect of γ-radiation of lettuce seeds (*Lactuca sativa* L.) for the yield and removal of macronutrients by plants

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Abstract. The effect of pre-sowing treatment with different doses of γ-radiation ^{60}Co on the development and yield of lettuce plants has been studied. For this purpose, the seed material was irradiated with ionizing radiation ^{60}Co in doses of 1-6 Gy; vegetation experiment was laid to determine the weight of plants, as well as the accumulation of dry matter, nitrogen, phosphorus, potassium. The values of stimulating and inhibitive doses have been established. It was determined that radiation hormesis was observed for lettuce plants at doses of 1 and 2 Gy: there was an increase in crop yield and maximum accumulation of the main elements of mineral nutrition. A dose of 6 Gy inhibited the growth and development of lettuce plants; at this dose of radiation, not only a decrease in yield occurred, but also a decrease in phosphorus and potassium removal.

1 Introduction

Radiation technologies can be used to increase productivity, crop quality and plant resistance to diseases and various stressful conditions. The combined use of fertilizers and radiation of seed material with different doses of ionizing radiation can increase the production of agricultural products, improve their quality, shelf life, which makes it possible to solve one of the most important tasks for ensuring food security in Russia today.

It should be noted that stimulating effects appear only when exposed to moderate doses of ionizing radiation, which are specific for each plant species and depend only on the physiological state of crops. As a rule, for the manifestation of radiation hormesis, it is recommended to expose seeds to radiation in doses from 3 to 40 Gy [1]. When the seed is radiated with higher doses, the growth and development of plants is inhibited. Therefore, it is very important to establish low and high dose ranges for each crop. In our work, the lettuce crop was chosen as the object of research. It was not by chance that the preference was given to this crop. Lettuce is freely cultivated in all countries of the world, and is also considered one of the traditional vegetable crops of many peoples. It contains a sufficient amount of mineral salts, organic acids, vitamins, enzymes. Due to its economic, nutritional, and medicinal qualities, lettuce is one of the most valuable vegetable crops.

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The purpose of our research was to study the effect of pre-sowing seed treatment with different doses of ionizing radiation on the development and yield of lettuce plants (*Lactuca sativa* L.) of the Moscovskiy Parnikoviy variety in doses of 1, 2, 3, 4, and 6 Gy. The tasks of the study were to establish stimulating doses of γradiation ^{60}Co on such indicators as: crop yield, content of dry matter, nitrogen, phosphorus, potassium in plants, as well as removal of the main elements of mineral nutrition by lettuce.

2 Materials and Methods

In 2021, a vegetation experiment was conducted at the Department of Agronomic, Biological Chemistry and Radiology of the Russian State Agrarian University – Moscow Agricultural Academy named after K.A. Timiryazev (Russia, Moscow) on the study of the effect of pre-sowing treatment with different doses of ionizing radiation on the development and yield of lettuce plants of the Moscovskiy Parnikoviy variety. This variety was bred at the All-Russian Scientific Research Institute of Breeding and Seed Production of Vegetable Crops (Russia, Moscow region) and entered into the state Register in 1955. The experiments were carried out on sod-podzolic medium loamy soil selected from the experimental field of the Russian State Agrarian University – MAA named after K.A. Timiryazev (Moscow, Russia), which was characterized by the following agrochemical indicators: pH_{KCl} – 5.1; hydrolytic acidity – 3.3 mg-eq/100 g of soil; the amount of absorbed bases – 28.0 mg-eq/100 g of soil; saturation efficiency with bases – 89.5%. The provision of the soil with mobile phosphorus and exchangeable potassium (according to Kirsanov) was at the level of class IV [2].

The experiment scheme included 6 variants in four-fold repetition. Before sowing, the seeds were irradiated at the All-Russian Research Institute of Radiology and Agroecology (Obninsk, Russia). The gamma radiation unit GUR-120 was used. Source of γ-radiation - ^{60}Co (type III GIK 7-4). To determine the radiation dose, a universal dosimeter DKS-101 with an ionization chamber BMK-50 No. 1198 (Polytechform-M, verification certificate No. 6227 (PJSC PZ Signal, registration number in the register of accredited persons RA.RU.311660) was used. The seeds were radiated in doses of 1, 2, 3, 4, and 6 Gy. The next day after radiation, the vessels were filled, in which mineral fertilizers were additionally applied in doses of 150 mg/ kg of soil N, 150 mg/ kg of soil P_2O_5, and 200 mg/kg of soil K_2O, also a full dose of lime was added to the soil, which was calculated by the hydrolytic acidity value [3]. Sowing was carried out in the amount of 75 seeds of lettuce of the Moscovskiy Parnikoviy variety per vessel. After making sure that the plants had developed sufficiently, and counting the number of plants in each vessel, thinning was carried out to 15 pieces per vessel. After that, the samples that were removed from the vessel were dried to a constant weight and placed in containers for further studies. At the end of the growing season, the herbage of lettuce was cut off with scissors. The plants were weighed, part of the material was selected for analysis of raw material, the rest was placed in paper bags, signed, and dried to a constant weight at a temperature of 105°C. After that, the dried plant material was crushed using a mill and transferred to small vessels for hermetic storage and further research.

In lettuce plants, the content of mineral nutrition elements was determined by the following methods: nitrogen – by Kjeldahl, phosphorus – by E. Truog and A. Meyer, potassium – by flame-photometric method [2].

The germination energy and germination ability of seeds of lettuce of the Moscovskiy Parnikoviy variety were determined according to GOST 12038-84 [4].

3 Results and Discussion

Studies have shown that lettuce seeds had good germination ability (98-99%) and high germination energy (96-98%). Both of these parameters did not depend on the radiation dose (Fig. 1).

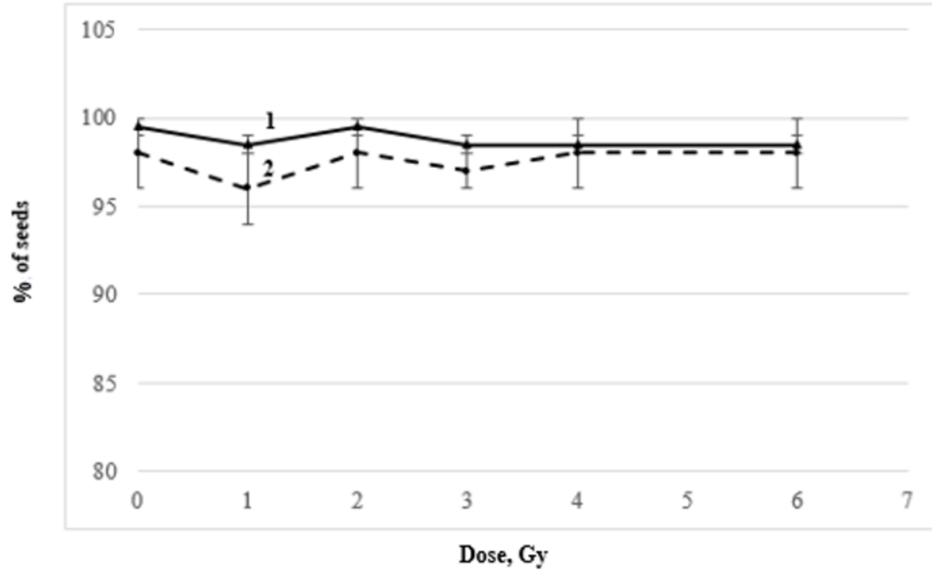

Fig. 1. The effect of different doses of γradiation (^{60}Co) on germination ability (1) and germination energy (2) of lettuce seeds of the Moscovskiy Parnikoviy variety (Compiled by the authors).

Nevertheless, according to the data obtained, pre-sowing treatment of seeds with different doses of ionizing radiation affects the growth and development of lettuce plants (Table 1).

The stimulating effect of radiation was reliably observed when radiating seeds at doses of 1 and 2 Gy. The yield of lettuce plants of the Moscovskiy Parnikoviy variety in these variants was 8.98 g/vessel and 10.07 g/vessel, which is 9.78% and 23.11% higher than the control variant (Fig. 2). When radiating the seed material at doses of 3 and 6 Gy, there was a statistically significant decrease in the lettuce yield. The inhibitory effect of radiation was observed here. The dry weight of plants in the indicated variants was 7.28 g/vessel and 6.28 g/vessel, respectively, that is, 11-23.23% lower than the control.

The total nitrogen removal by lettuce plants was in the range of 12.3 mg/vessel – 18.8 mg/vessel. The smallest removal of this mineral nutrition element was noted when the seed material was irradiated with γ-radiation (^{60}Co) at a dose of 6 Gy, as well as in the control version. Statistically significant differences in the obtained values of nitrogen removal were not recorded. Nevertheless, when radiating lettuce seeds with doses of 2 and 4 Gy, there is a significant increase in the use of nitrogen by plants, where the economic removal of this food element exceeded the control values from 29.71% to 37.23% (Fig. 3), namely, it was 17.8 mg/vessel – 18.8 mg/vessel. It should be noted that the nitrogen content during radiation of the seed material with doses of 2 and 4 Gy also significantly increases.

Table 1. The effect of pre-sowing treatment with different doses of ionizing radiation on the growth and development of lettuce plants of the Moscovskiy Parnikoviy variety.

Variant, radiation dose, Gy	Dry weight, g/vessel	Removal, mg/vessel		
		N	P_2O_5	K_2O
0	8.18	13.7	3.67	21.5
1	8.98	15.3	4.93	23.2
2	10.07	17.8	3.78	30.3
3	7.28	14.5	2.73	20.6
4	7.95	18.8	3.97	23.7
6	6.28	12.3	2.03	16.8
LSD_{05}	0.53	1.9	0.64	1.8

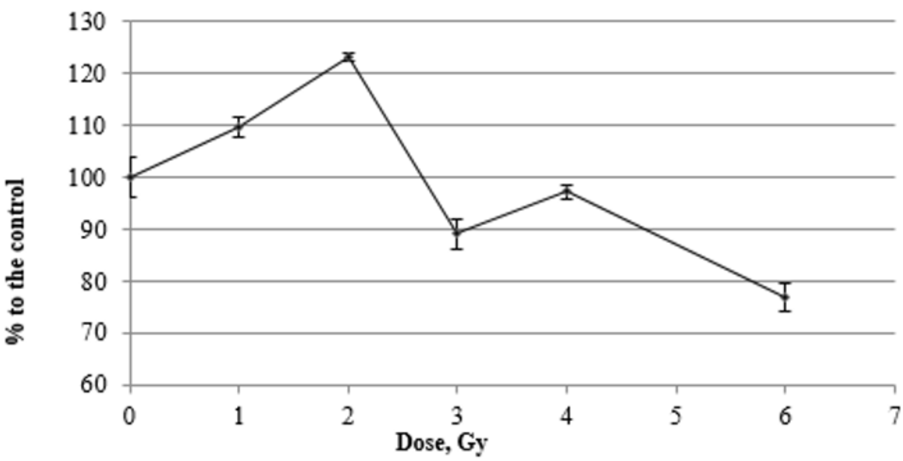

Fig. 2. The effect of different doses of γ-radiation (^{60}Co) on the accumulation of dry matter in lettuce plants of the Moscovskiy Parnikoviy variety (Compiled by the authors).

Research results have shown that lettuce makes good use of phosphorus from sod-podzolic soil. The macronutrient removal was in the range of 2.03 mg/vessel – 4.93 mg/vessel. A statistically significant increase in the use of phosphorus was observed when the seed was radiated with ionizing radiation at a dose of 1 Gy, where the effect of radiation hormesis was recorded. The removal of the mineral nutrition element in this variant was 4.93 mg/vessel, which is 34.33% higher than the control. Inhibitory effect of γ-radiation (^{60}Co) was reliably established when radiating lettuce seeds with doses of 3 Gy and 6 Gy, where a decrease in consumption of this mineral nutrition element was observed by 25.61% - 44.69% compared with the control variant (Fig. 3). Phosphorus removal here was 2.03 mg/vessel and 2.73 mg/vessel.

The unequal use of potassium by lettuce plants was observed when radiating the seed material with ionizing radiation. The stimulating effect of radiation was noted at the received doses of 2 and 4 Gy, where the removal of potassium by plants was maximum and amounted to 30.3 mg/vessel and 23.7 mg /vessel, which significantly exceeds the values of the macronutrient removal in the control variant by 10.13% - 40.73%. It should be noted that the treatment of lettuce seeds by γ-radiation (^{60}Co) statistically significantly reduces the removal of potassium in plants at a dose of 6 Gy. The removal of the mineral nutrition element in this variant was 16.8 mg/vessel, 21.92% lower than the control (Fig. 3).

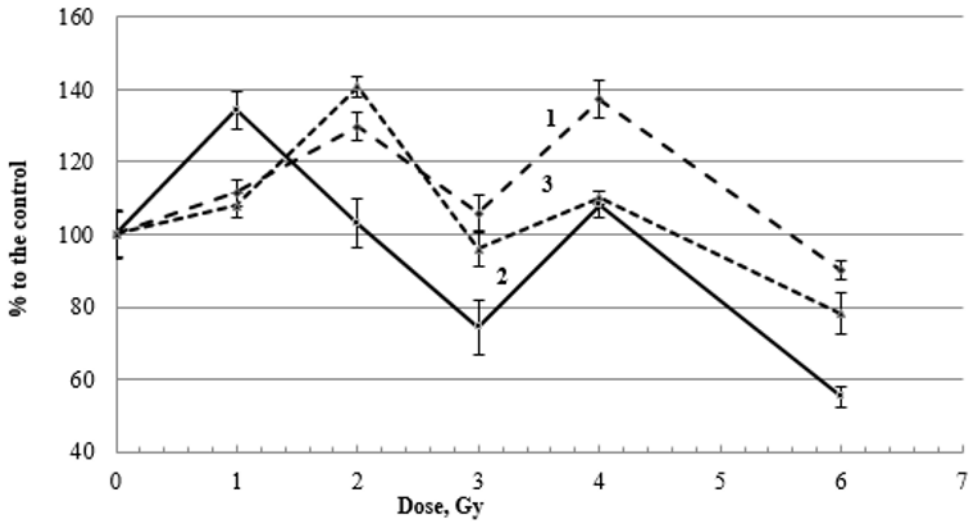

Fig. 3. The effect of different doses of γ-radiation (^{60}Co) on the removal of mineral nutrition elements in lettuce plants of the Moscovskiy Parnikoviy variety: 1. removal of nitrogen; 2. removal of phosphorus; 3. removal of potassium. (Compiled by the authors).

Table 2. The effect of pre-sowing treatment with different doses of ionizing radiation on the content of dry matter and macronutrients in lettuce plants of the Moscovskiy Parnikoviy variety, %.

Variant, radiation dose, Gy	Dry matter	N	P_2O_5	K_2O
0	4.000±0.152	0.170±0.008	0.045±0.003	0.260±0.015
1	4.310±0.084	0.170±0.007	0.055±0.003	0.260±0.010
2	5.000±0.039	0.180±0.006	0.038±0.003	0.300±0.008
3	3.660±0.106	0.200±0.004	0.038±0.003	0.280±0.006
4	4.050±0.057	0.240±0.012	0.050±0.004	0.300±0.005
6	3.450±0.091	0.200±0.005	0.033±0.003	0.270±0.015

The conducted vegetation experiment on sod-podzolic medium loamy soil confirmed that stimulating effects are manifested when treated with ionizing radiation of plants only in doses determined for each species (Table. 2; Fig. 4). Thus, radiation of seeds at a dose of 2 Gy statistically significantly increases the dry matter content in the lettuce of the Moskovskiy Parnikoviy variety. The dry weight of plants in the indicated variant was 5.00%. In other variants, no significant increases in the dry matter content were observed. It should be noted that exposure to radiation affects the metabolism in plants, while there is an increase in the content of mineral nutrition elements. The nitrogen content in the lettuce of the Moscovskiy Parnikoviy variety ranged within the limits 0.17 – 0.21%. The smallest amount of nitrogen was observed in the control variant and when radiating the seed material with doses of 1 and 2 Gy, namely 0.17 and 0.18%, respectively. A statistically significant increase in the nitrogen content in plants was noted in variants when seeds were treated with radiation doses of 3, 4, and 6 Gy. In these variants, the nitrogen content was

0.20 - 0.24%. The phosphorus content in lettuce plants was in the range of 0.033 – 0.055%. Stimulating effect of γ-radiation (^{60}Co) was observed at a dose of 1 Gy, where a significant increase in the phosphorus content reached 0.055%, the effect of different radiation doses is also observed on the potassium content in lettuce plants. The effect of radiation hormesis was observed when seeds were irradiated with γ-radiation (^{60}Co) in doses of 2 and 4 Gy, where the potassium content was 0.30% each.

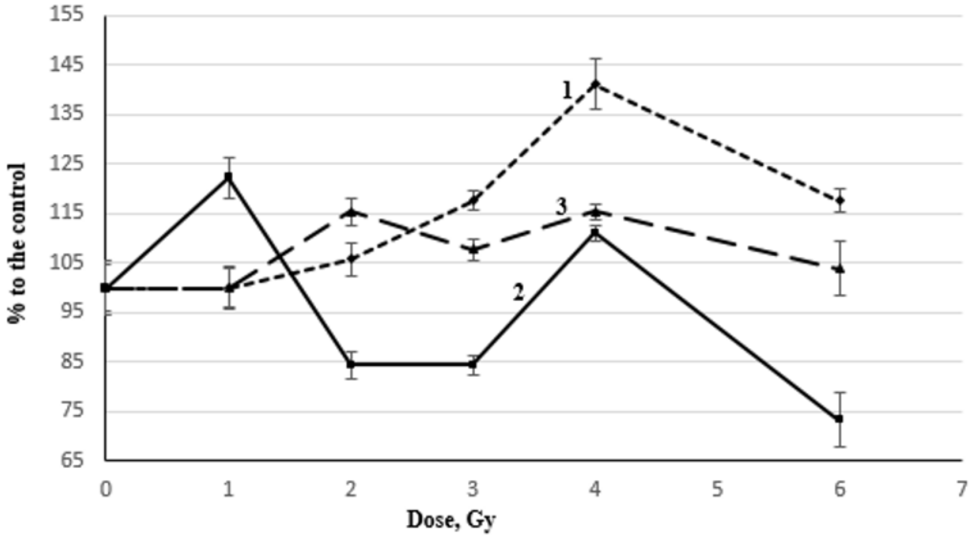

Fig. 4. The effect of different doses of γ-radiation (^{60}Co) on the content of mineral nutrition elements in plants of lettuce of the Moscovskiy Parnikoviy variety: 1. nitrogen; 2. phosphorus; 3. potassium. (Compiled by the authors).

An increase in seed germination ability, the biological potential of the seed material, crop yields, product quality, as well as acceleration of plant growth and development can be achieved by pre-sowing treatment with ionizing radiation [5]. The positive effect of such treatment can be designated as eustress, in which the effect of radiation hormesis is observed. The negative effect of high doses of ionizing radiation is like distress. The theory of eustress can be attributed to the acceleration of the intensity of seed germination, shortening the duration of the early stages of crop development, elongation of the root system of plants, an increase in the top mass, which entails a high increase in yield [6], which we observed when ionizing radiation was applied to lettuce plants in doses of 1 and 2 Gy, where the maximum yield of the studied crop was obtained (Table 1).

It should be added that the radiation of seeds with ionizing radiation also affects the exchange processes, because of which the quality of crop production is improved. Thus, the amount of protein in the grain of cereals increases, the sugar content in sugar beets, starch in potato tubers, vitamins in vegetables. Many researchers [1, 7, 8, 9] note that the intensity of gene expression increases with radiation hormesis. When radiating the seed material, the main metabolic pathways are preserved, evolutionarily fixed and characteristic of a particular plant organism. For example, sunflower increases the accumulation of fat in seeds, and sugar beet – sucrose. Therefore, the strengthening of the individual development of the plant organism caused by the effect of ionizing radiation leads to the synthesis of precisely those substances for the production of which this plant species is evolutionarily adapted. In vegetable products, the consumption of phosphorus and potassium by plants increases, which contributes to better sugar accumulation. Thus, when processing seed material with doses of 1 and 2 Gy, the content of phosphorus and potassium in lettuce plants increases (Table. 2), therefore, it can be assumed that an increase in the sugar content will also be observed in this dose range.

When the seed material is treated with ionizing radiation, the radiation energy is converted into reactive oxygen species [8]. Such molecules with very high reactivity with excessive accumulation can cause oxidative stress, which can manifest in stunting the growth and development of plants [9, 10]. It was the decrease in yield that we observed when exposed to γ-radiation (^{60}Co) for lettuce seeds starting from a dose of 3 Gy (Table 1). It should be emphasized that reactive oxygen species at absorbed low doses appear in sufficiently small volumes that cannot harm the plant. Such oxygen forms can bind with low molecular weight organic compounds that have regulatory functions, activate the germination of seed material and the subsequent development of agricultural crops [11, 12], which we noted in this paper. At absorbed doses of 1 and 2 Gy, the yield of lettuce, the content of dry matter, phosphorus, potassium in it, the removal of mineral nutrition elements by the green culture increase (Tables 1, 2; Fig. 3, 4).

4 Conclusions

With γ-irradiation (^{60}Co) of the seed material at doses of 1 and 2 Gy, a significant increase in the yield of lettuce was observed, with the largest dry weight of plants, as well as a statistically significant increase in the dry matter content were obtained when treating seeds at a dose of 2 Gy. The phosphorus content in the agricultural crop and the removal of this element of mineral nutrition were the highest at the received dose of 1 Gy. As for the nitrogen content in lettuce, stimulating effects were obtained from higher absorbed doses. When radiating seeds with doses of 3, 4, and 6 Gy, there was a significant increase in nitrogen accumulation in plants, and the removal of the organogenic element was the greatest at a dose of 4 Gy. Nevertheless, it is worth noting that it is necessary to find out which compounds include this nitrogen. It can be assumed that there is an increase in the content of non-protein nitrogen, namely the nitrate form, which will negatively affect the quality indicators of lettuce. Pre-sowing treatment with γ-radiation ^{60}Co at a dose of 2 Gy also statistically significantly increases the removal of nitrogen by the green crop, the content and removal of potassium by the crop, for which a dose of 4 Gy is stimulating. The yield of lettuce plants is negatively affected by seed treatment with doses of ionizing radiation of 3, 4, 6 Gy, which significantly inhibit the growth and development of agricultural crops. The removal of phosphorus and potassium is statistically significantly reduced at the received dose of 6 Gy.

Thus, it was found that for radiation stimulation of seeds of lettuce of the Moscovskiy Parnikoviy variety, it is necessary to use a dose range of 1-2 Gy. With an increase in the radiation intensity, the growth and development of plants deteriorates, there is a decrease in the yield of green crop and its quality.

It should be noted that the probability and scale of practical application of seed treatment with stimulating doses of ionizing radiation will be determined to a greater extent by a stable increase in crop yields, improvement in the quality of crop production, as well as by testing the operability of this method in specific soil and climatic conditions with the mandatory use of zoned varieties. The combined use of chemicals, namely mineral and organic fertilizers, and radiation technologies will allow achieving scientific and technological progress in agriculture.

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