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An Investigation of the Effects of X-Ray Treatment on the Concentration of Reducing Sugars in Potatos and Their Sprouting

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Abstract—This study investigates the effect of X-rays on potato tubers to stop their sprouting at different periods of storage. It has been found that there is a connection between the period of storage and the dose of irradiation. To control the quality of the irradiated tubers, the concentration of reducing sugars was measured during the entire experiment and compared to the parameters of non-irradiated potato tubers.

Keywords: X-ray irradiation, inhibition of potato sprouting, reducing sugars.

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INTRODUCTION

According to the data of the Russian Presidential Academy of the National Economy and Public Administration, more than 33.6 million metric tons of potatoes were harvested in Russia in 2015 and 31 million metric tons were harvested in 2016. In connection with these large volumes, there is a need for long-term storage of potatoes until the next harvest.

One of the main problems of potato storage is sprouting, which leads to tubers losing their shape, moisture, and nutrients. Agricultural practice uses large doses of chemical pesticides to suppress tuber sprouting during storage. However, pesticides accumulate in the tubers. In addition to the chemical treatment, producers store potatoes at low temperatures from 5° to 8°C, which slows tuber sprouting. However, at these temperatures the sugar content increases in potatoes, which can negatively affect their further thermal processing; the potatoes darken and acquire a bitter taste. Thus, the need for alternative methods for protection of potatoes during their long-term storage arises.

Radiation treatment of potato tubers is an effective method for inhibition of sprouting. Gamma rays are used worldwide for irradiation of different vegetables and fruits, including potatoes, to extend the storage period [1–5]. There have been studies on the influence of gamma radiation on the biochemical, morphological, and structural properties of the potato. It was demonstrated in [6] that a dose from 50 to 150 Gy does not affect the food value and organoleptic properties of the potato. Moreover, these doses make it possible to significantly increase the storage period. In [5], potato tubers were treated with doses from 50 to 150 Gy at 10, 30, and 50 days after the potatoes were harvested. It was shown that early treatment with gamma rays at higher doses significantly inhibits sprouting. In addition, the temperature at which potatoes are stored is important: the higher the temperature is the lower the dose is that is required to stop sprouting. Tubers that were irradiated with doses of 150 Gy had a significant decrease in ascorbic acid compared to lower doses. In [7], the antioxidant properties of a group of enzymes were studied in potatoes after exposure to gamma radiation at 30–200 Gy; it was found that the dose of 50 Gy inhibited tuber sprouting with the enzyme activity being the best compared to other irradiation doses. In [8], different methods to stop potato sprouting, including gamma irradiation and treatment with different essential oils and iodide, were compared. It was found that the radiation treatment was more effective compared to the chemical methods with the minimum effect on the biochemical indices of the tubers.

Electron beams are an alternative to gamma radiation and chemical treatment for inhibition of potato sprouting [9–11]. In [9] it was shown that tuber exposure to electrons with an energy of 270 keV stopped potato sprouting, with the amount of sugars in the irradiated tubers decreasing 3 months after the irradiation compared with the sugar level before treatment. It was shown in [11] that the exposure of potatoes to a beam of accelerated electrons with an energy of 1 MeV and at doses that exceed 40 Gy was an effective method for inhibition of sprouting.

The purpose of this study was an experimental investigation of the effect of X-rays on the sprouting of potato tubers at different periods of storage.

1. MATERIALS AND METHODS

1.1. Objects of the Study and Experimental Design

The objects of research were 100 kg of potato tubers of the Zhukovskii rannii variety of the 2016 harvest with a mass of 100–120 g that were grown at the Lorkh All-Russian Potato Institute and harvested on August 20, 2016. The experiment was carried out in four stages. At the first stage, 198 tubers were arbitrarily selected and exposed to X-rays 2 months after the harvest. At the second stage, 176 tubers were exposed to X-rays after 3 months of storage. The third stage was at 4 months of the storage (154 tubers), while the fourth stage was irradiation 5 months after the harvest (132 tubers). Irradiation at later periods was not reasonable, since a third of the potatoes that had not been irradiated started to sprout by January 2017 and almost all tubers had started to sprout by February 2017. The experiments and potato storage were performed at 12–15°C.

During the entire experiment from September 2016 to March 2017 we monitored the kinetics of sprouting of the irradiated tubers and compared it with the kinetics of the control non-irradiated specimens. To control the quality of the potato tubers of all the four stages of irradiation, every month we measured the concentration of reducing sugars 3–4 days after irradiation. At the same time, we measured sugars in the tubers that were irradiated earlier. The data were also compared with the sugar concentration in the control non-irradiated specimens.

1.1.1. Irradiation of Potato Tubers

The potato tubers were exposed to X-rays; the source was a PUR5/50 power source with a BSV-23 X-ray tube and molybdenum anode. The tube current in all the experiments was 20 mA, the voltage was ~50 kV, and the operating power of the tube was 1 kW. The irradiation was performed using four windows of the tube at the same time. Each tuber was located at a distance of 11 cm from the window of the X-ray tube. The irradiation duration was varied: 4, 8, 12, 16, 20, 24, 28, 32, 40, and 50 min; all the tubers were irradiated during half of the time on one side; they were then turned to the other side to achieve homogeneous irradiation.

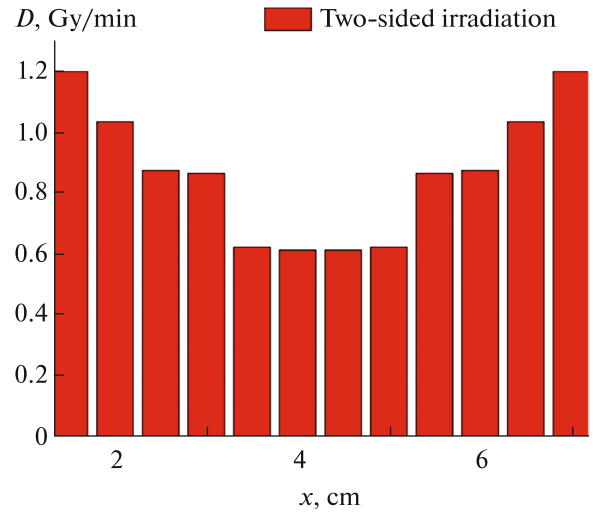

Fig. 1. The distribution bar chart of the dose rate (*D*) with respect to the depth (*X*) during propagation of X-rays through an aqueous sphere with a radius of 3 cm that is irradiated from two opposite sides.

1.1.2. Calculation of the Dose Absorbed in the Tuber

The GEANT4 program complex was used to assess the dose that was absorbed in the potato. When the propagation of X-rays through the potato was simulated the technical characteristics of the X-ray tube that was used and the scheme of irradiation of the potato were taken into account. All the parameters of the X-ray tube were obtained from the manufacturer and reproduced in the program with an accuracy to 0.1 mm.

In the simulation it was assumed that an electron beam with an energy of 50 keV that had two billion particles fell onto a cylindrical molybdenum anode. The cross section of the beam was a rectangle with a size of 1 × 10 mm. We took the facts into account that the X-ray tube has a lead case and the photons left it via a beryllium window. The potato tuber was simulated by an aqueous sphere with a radius of 3 cm. To assess the dosimetric distribution with respect to the depth, the sphere was divided into 12 0.5-cm layers. The result of the simulation of the two-sided irradiation of the potato with X-rays taking the bremsstrahlung spectrum that was calculated using the GEANT4 program complex into account was the distribution of the rate of the absorbed dose *D* with respect to the penetration depth *X* of the X-rays (Fig. 1).

These conditions made it possible to calculate the total absorbed-dose rate in an aqueous sphere with a radius of 3 cm. It was found that the dose rate in the potato tuber with an average mass of 120 g was approximately 0.01 Gy/s. Thus, at the exposures that were used the potato was irradiated with doses of 2.4, 4.8, 9.6, 12, 14.4, 16.8, 19.2, 24, and 30 Gy, respectively.

As can be seen from Fig. 1, the dose that was absorbed in the outer layers of the sphere was higher than in the inner layers. In the potato tubers, sprouts lie at the depth from 2 to 5 mm depending on the variety; thus, at these characteristics of the irradiation the growing points of the potato were irradiated uniformly.

1.1.3. The Method for Determination of the Concentration of Reducing Sugars Using Dinitrosalicylic Acid (DNS)

The concentration of reducing sugars (RSs) in the potato tubers was determined by a colorimetric technique using dinitrosalicylic acid (DNS). An extract was isolated from each potato tuber, which was centrifuged to obtain pure juice; a 1 : 20 dilution with distilled water was then carried out. The samples with the diluted extract were then supplemented with DNS at 1 : 3 and incubated in a boiling water bath for 5 min. The samples were cooled to room temperature and their optical density was determined using a spectrophotometer at 540 nm as an excess of the optical density of the sample with the extract over the optical density of the background DNS solution. The obtained optical densities were recalculated to the concentrations of reducing sugars in g/L using calibration curves and the dependences of the concentrations of reducing sugars C on the irradiation dose D were plotted for each stage.

2. RESULTS AND DISCUSSION

2.1. Potato Tuber Sprouting after Exposure to X-Rays

To study the kinetics of potato sprouting, the sprout length in irradiated and control tubers was measured every month throughout the entire experiment. The obtained values were used to plot the dependences of the average total sprout length per tuber L/N that was measured at different periods after the irradiation for each stage on the irradiation dose D.

Figure 2 gives the dependences of the total sprout lengths of tubers that are normalized with respect to the number of tubers L/N and measured 7 months after the harvest, that is, in March 2017, on the irradiation dose D for all the four stages of the tuber exposure to X-rays. It can be seen that with an increase in the irradiation dose the total sprout length per tuber decreased, with the dose dependences being nonlinear. For the potato tubers that were irradiated in October (stage 1), the sprouting was inhibited at a dose rate that exceeded 15 Gy. The potato tubers that were irradiated in November and December (stages 2 and 3) with doses from 15 to 20 Gy or higher did not sprout during the entire observation period. The tubers that were irradiated in January (stage 4) had sprouting inhibited at a dose of 30 Gy.

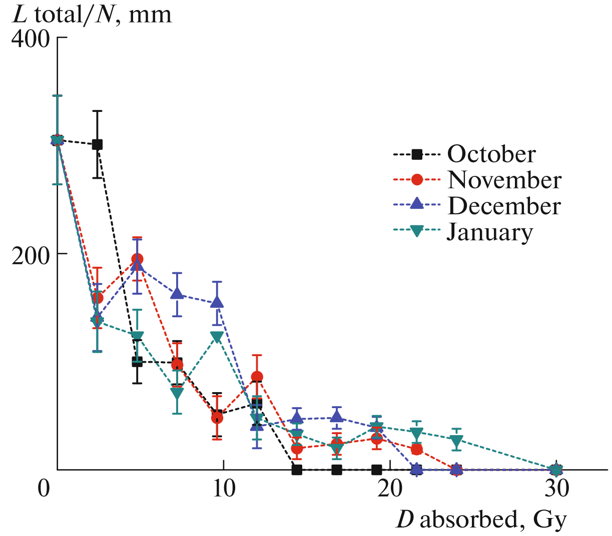

Fig. 2. The dependence of the total sprout length that is normalized to the number of the tubers L/N on the irradiation dose D for all the four stages of the tuber treatment with X-rays 7 months after the harvest.

2.2. The Relationship between the Concentration of Reducing Sugars and the Kinetics of Sprouting in Control Non-Irradiated Tubers

Figure 3a gives the dependence of the concentration of reducing sugars on the storage period for control (non-irradiated) tubers; Fig. 3b gives the kinetics of their sprouting during the entire observation period.

As can be seen from Fig. 3a the concentration of the sugars in the tubers almost did not change from October until December and was approximately 2.0 ± 0.5 g/L; during this period the tubers did not sprout (Fig. 3b). There was a sharp jump in the sugar concentration to 14 ± 1 g/L in January, which initiated tuber sprouting (Fig. 3b). In February and March, the concentration of reducing sugars decreased to the initial values (Fig. 3a); the potatoes continued to sprout. After 7 months of storage the average sprout length was approximately 186 ± 5 mm.

It can be seen that the sugar concentration in the control non-irradiated tubers changed throughout the entire observation period.

2.3. The Concentration of Reducing Sugars in Tubers Irradiated at Different Periods of Storage

Based on the investigation that was performed from October to December 2016, that is, at 3–5 months of storage, it was found that the sugar concentration increased after the irradiation in the first three stages compared to the control samples, with the maximum

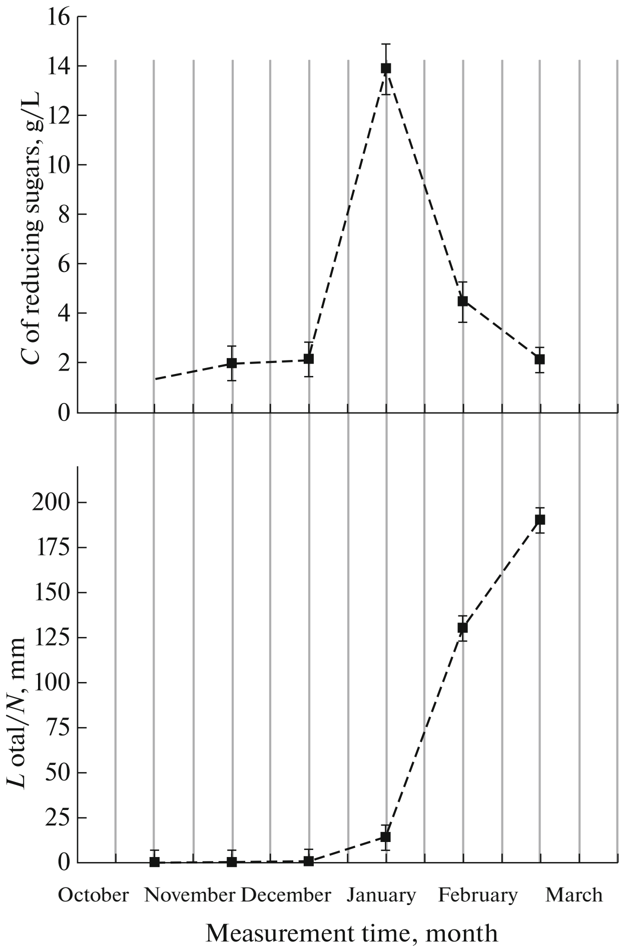

Fig. 3. (a) The dependence of the concentration of reducing sugars (C) in non-irradiated tubers on the period of the potato storage (t); (b) The dependence of the average total sprout length per one control tuber N/L on the period of the potato storage (t).

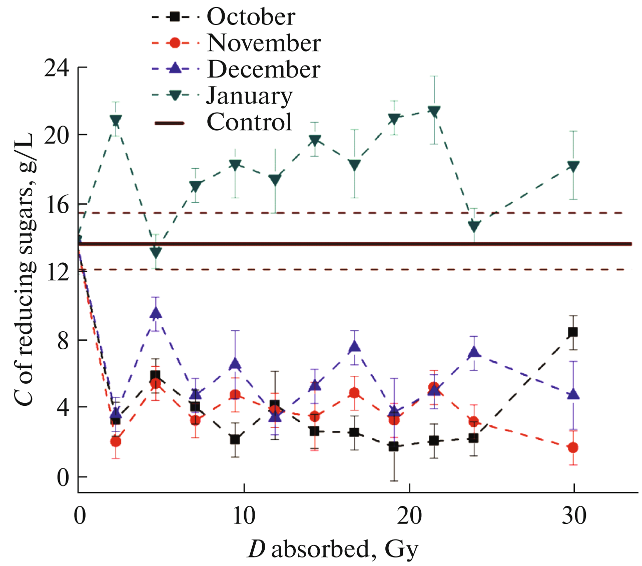

Fig. 4. The dependence of the concentration of reducing sugars C that was measured in January 2017 on the absorbed dose D in tubers that were irradiated in October, November, and December.

sprouting at each stage observed 1 month after the irradiation. In addition, no explicit dependence was observed for the dose range from 2.4 to 30 Gy. However, by December 2016 the sugar concentration in the tubers that were irradiated in October was almost the same as in the control samples ($\approx 2.0 \pm 0.3$ g/L). The maximum deviation from the control values during the indicated period was observed in December 2016 in the tubers that were irradiated in November (to 8.0 ± 0.7 g/L), that is, 1 month after the irradiation.

Figure 4 gives the dependences of the concentrations of reducing sugars in the tubers that were irradiated in October, November, December, and January with the concentrations measured in January 2017. In January, the sugar concentration in the control samples reached the maximum of 14 ± 1 g/L for the entire observation period. It can be seen from Fig. 4 that the sugar concentration in the tubers that were irradiated in January was, on average, higher than the control values and reached 21 ± 1 g/L. In the tubers that were irradiated in October and November, the sugar concentration C ranged from 2 to 5 g/L, while in the tubers that were irradiated in December the sugar concentration C ranged from 4 to 10 g/L. In February 2017, the sugar concentration in the irradiated tubers did not exceed 6.0 ± 0.5 g/L, that is, for the tubers that were irradiated in January the maximum concentration of reducing sugars was observed immediately after the irradiation.

By March 2017 all the control tubers had started sprouting, with the sugar concentration in the end point being 2.0 ± 0.5 g/L. The sugar concentration in the tubers that was measured in March 2017 for all the four stages ranged from 0.9 to 3.4 g/L. Thus, it can be stated that the concentration of reducing sugars in the irradiated and non-irradiated tubers almost coincided at the end point of the measurements by March 2017, after 7 months of storage.

CONCLUSIONS

In this study it was found that the X-ray exposure of potato tubers that were harvested in August and irradiated in October at doses that exceeded 15 Gy resulted in the inhibition of potato sprouting during the entire observation period. The potato tubers that were irradiated in November and December stopped sprouting at doses of 20 Gy, while the irradiation in January stopped sprouting at 30 Gy. Thus, the earlier the radiation treatment is carried out to inhibit sprouting, the lower the dose is that can be used for irradiation.

It was demonstrated that the concentration of reducing sugars in the control samples of the 2016 harvest almost did not change until December 2016 (≈2 ± 0.5 g/L) with a sharp jump in the sugar concentration to 14 ± 1 g/L observed in January and a further decrease to the initial values found in February and March 2017. The exposure to X-rays resulted in an increase in the concentration of reducing sugars in the potato tubers that were irradiated at different doses with the maximum found 1 month after each irradiation for the tubers that were irradiated in October and November. The maximum concentration of reducing sugars in them was 9.7 ± 1 g/L. For the potatoes that were irradiated in January, the maximum sugar concentration was observed immediately after the irradiation and was 21 ± 1 g/L; however, 1 month later the concentration was close to the control values. By March 2017, the concentration of reducing sugars in all the irradiated tubers was close to the control values for all the four stages of irradiation within the dose range from 2.4 to 30 Gy.

Based on the experimental data it can be concluded that the concentration of reducing sugars in the potato tubers that were exposed to X-rays 1 month after the harvest ranged from 0.9 to 9.7 g/L, whereas for the control non-irradiated tubers it ranged from 2 to 14 g/L during the entire observation period. The radiation treatment 5 months after the potato harvest led to an increase in the sugar concentration that exceeded the concentration in the non-irradiated tubers during the entire observation period, which indicates that the radiation treatment of the potato at more than 4 months after the harvest is not useful.

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