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Electron Beam Irradiation to Control *Rhizoctonia solani* in Potato

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Abstract: This study focuses on the influence of pre-planting irradiation on the development, health, and yield of seed potatoes infected with *Rhizoctonia solani*. The research was prompted by the need to ensure crop security and sustainability in the modern-day environment, which calls into question the future sufficiency of crop yields. Considering that the focus has shifted to non-chemical methods of crop treatment at all plant development stages in response to more stringent regulations governing potato production, it is particularly important to refine physics-based methods to suppress fungal diseases caused by *Rhizoctonia solani*. Irradiation of tubers with 20–150 Gy inhibited the potato development phases and the doses exceeding 150 Gy completely suppressed the potato sprouting. Doses ranging from 20 Gy to 100 Gy decreased the quantity of large tubers by 10–20% on average while the number of medium and small tubers increased by 5–15% and 3–10%, respectively. Irradiation of seed potatoes also decreased the sclerotia and non-sclerotia forms of diseases caused by *Rhizoctonia solani* in the harvested tubers. It was found that 1 MeV electron irradiation with doses ranging from 20 Gy to 30 Gy is the most efficient for the pre-planting treatment of seed potatoes since the penetration of low-energy accelerated electrons into the upper layers of potato tubers ensures the suppression of diseases caused by *Rhizoctonia solani* by at least 10% from the value of non-irradiated samples and prevents the reduction of total yield allowing for a maximum of 25% loss.

Keywords: cracks; deformity; dented spotting; electron beam processing; net necrosis; open field study; *Rhizoctonia solani* Kühn

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1. Introduction

Being easily adaptable to the ongoing change in global environmental conditions, economically viable potato is seen as a strategically important crop for global food security [1,2]. According to simulation studies conducted by [1–4], temperature growth and CO_2 fertilization will contribute to an increase of up to 20% in potential potato yield by 2050, provided that relevant adaptation measures are taken. Adaptation to new potato growth niches will involve not only selecting cultivars that can thrive in the local climatic and environmental conditions but also a higher focus on pre-planting treatment to curb the spread of weeds, parasites, and phytopathogens, which may substantially reduce crop yield, in particular, under greater ambient temperatures and in moist soils.

Considering that potato is expected to play a large role in the food supply chain since it is not only a staple food crop and fodder but also a key raw material for the production of starch, glucose, alcohol, and lactic acid, it is important to ensure a consistently high quality of seed potatoes. Global temperature growth and higher humidity will inevitably affect the development of seed material, causing various bacterial, viral, and fungal diseases triggered by *Phoma*, *Fusarium*, and *Rhizoctonia solani* to pervade throughout tubers [5–11].

Frequently occurring diseases caused by *Rhizoctonia solani* are widely spread in the world and, in particular, in Russia [12–14]. *Rhizoctonia* diseases can cause seed rot, root rot, and spots on the hypocotyl, thereby provoking plant growth retardation and even yield loss. Between 7% and 36% of potatoes are lost annually worldwide due to *Rhizoctonia*, with over 50% of crop yield lost each year being in Western Siberia [15–17].

Rhizoctonia diseases are primarily spread in deep soil layers where fungus can develop in the temperature range of +3 °C to +25 °C and can survive in a dormant state for up to 3–4 years. High humidity as well as high-density planting contribute to the development of *Rhizoctonia* diseases on potato tubers [18–20].

The rapid growth of fungal infections is directly attributed to the global upsurge in the quantity of diseased plants and weeds which contaminate the crops grown in the area. In Siberia's arable soils, for example, there are 0 to 20 pathogens per 100 g of dry soil, and the soils are more diseased where potatoes are grown since infected potato tubers contaminate the soil and roots of adjacent plants. The probability of pathogen spread through infected tubers ranges from 29% to 70%, and it increases to over 86% with high air humidity if airborne droplets are involved in the transmission [21].

Ways to combat infectious diseases in agriculture include the selection of disease-resistant plant species, crop rotation, and the use of chemical fertilizers and pesticides [22]. Though non-organic pesticides, herbicides, and fertilizers used in the industry have high performance in the fight against pests and various plant infections, they have a negative impact on the plants, beneficial microorganisms, and soil, and make pathogens resistant to the chemical substances [23–25].

With the growing environmental concern and more stringent regulations governing the use of agricultural chemicals, food irradiation has become a global trend [26–32]. As prescribed by ISO 14470:2011 [33], three types of irradiation are used in the food industry: gamma radiation emitted by isotopes ^{60}Co and ^{137}Cs, electron beams with energy up to 10 MeV, and bremsstrahlung radiation with energy up to 5 MeV generated by electron accelerators. In food irradiation, completely different effects can be achieved by varying the absorbed dose. In potatoes, irradiation doses of less than 20 Gy can increase the germination rate during pre-planting, while doses ranging from 50 Gy to 150 Gy inhibit the sprouting of harvested potatoes [26–30]. Scabs and rot in harvested potatoes are partly inhibited by doses under 150 Gy. A further increase in the dose, which cannot exceed 1 kGy under Global Harmonization Initiative, 2018, however, may have a harmful effect on potato tubers due to the inhibition of tuber cell immunity [34].

Considering that the penetration depth depends on the type of radiation as well as the energy of particles, different irradiation methods are used to achieve a specific objective. For example, potatoes infected with non-sclerotia diseases caused by *Rhizoctonia solani*, which pervades the entire tuber, require gamma irradiation, while potato tubers infected with sclerotia diseases found on the surface of the tuber should be treated with low-energy electrons as they penetrate the surface layers [35,36].

The aim of the experiment was to evaluate the influence of 1 MeV accelerated electrons on the productivity and phenology of potato tubers infected with *Rhizoctonia solani*.

2. Materials and Methods

2.1. Research Stages

The current research was conducted on naturally infected Lina seed tubers, grown at the Siberian Federal Scientific Centre of Agrobiotechnologies under the Russian Academy of Science, to inhibit *Rhizoctonia solani* Kühn (*R. solani*) in harvested potatoes. Identical Ø

(40 ± 5) mm tubers with a depth of axillary buds of around 2 mm were selected for the experiment to ensure the uniformity of data obtained during the study (Figure 1a). Eighty seed tubers were monitored after irradiation with ten doses ranging from 0 Gy to 3000 Gy to study a wider dose range of pre-planting irradiation (Figure 1b).

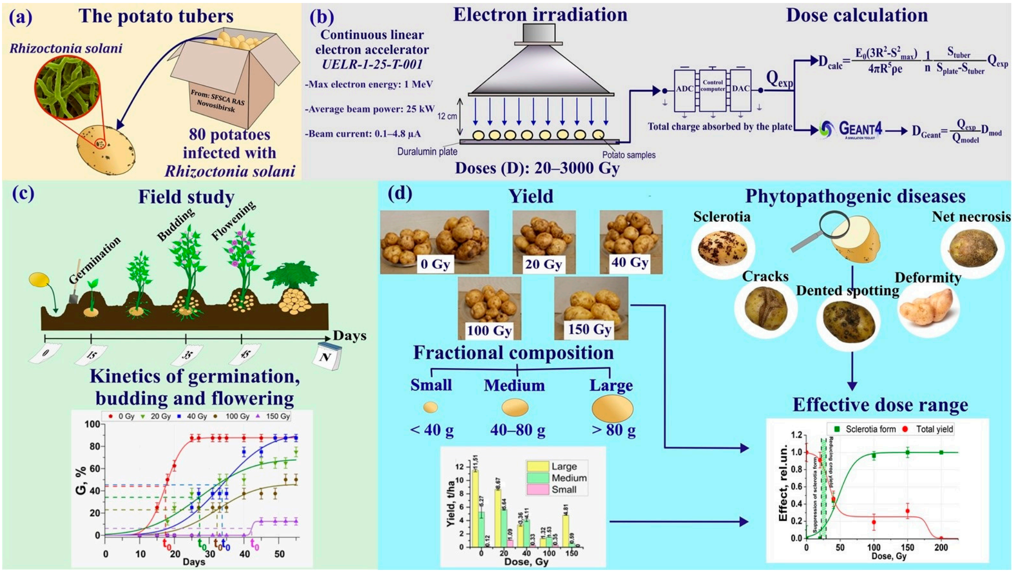


Figure 1. Stages of the research: (**a**) objects of the study; (**b**) electron beam irradiation; (**c**) field study; (**d**) analysis of phytopathogenic diseases of the new crop.

Field studies were carried out under soil and climatic conditions typical for the forest-steppe zone of Western Siberia. After planting the tubers, the research team recorded the number of days required for the onset of germination, budding, and flowering phases of plants (Figure 1c).

Further into the research, after estimating the yield, the team performed a fractional analysis of the tubers and assessed the degree of damage caused by *Rhizoctonia solani* (Figure 1d).

2.2. The Object of the Study

Potato variety: Lina; pedigree: *S. andigenum 1793* × *S. rybini* × *Anco*. The Lina potato is the mid-early variety selected by SIBNIIRS (SIBNIIRS, Krasnoobsk, Russia) and zoned for five regions of Russia: Northern Caucasus, Ural, Western Siberia, Eastern Siberia, and Far East. The starch content in the Lina potato is 14–20%. This potato variety is resistant to cancer, late blight, macrosporiosis, and mosaic viruses [37].

The seed potatoes were selected for the study from a batch of potatoes infected with *Rhizoctonia solani*. The potatoes which were found to be fit for the study had visible traces of sclerotia, net necrosis, dented spotting, deformity, and cracks [38]. To ensure irradiation dose uniformity for a higher validity of the research, the seed tubers involved in the study had a uniform size of Ø (40 ± 5) mm. The *Rhizoctonia solani* strains included in the research are most common for Western Siberia and belong to anastomosis group Ag-3, subgroups SP-23 and SP-25 isolated from infected soil, and group Ag-4, sub-groups SK-14 and SK-20 isolated from sclerotia found in tubers.

2.3. Electron Irradiation

Potato tubers were exposed to electron irradiation at 20 °C using a continuous linear electron accelerator UELR-1-25-T-001 with a maximum beam energy of 1 MeV and an average beam power of 25 kW (SINP MSU, Moscow, Russia). Figure 2 shows the irradiation method for eight tubers placed on the 35 cm·5.2 cm duralumin plate located 12 cm away from the electron beam exit window. The method involved the irradiation of 8 potatoes with the same dose, with one irradiation session for each dose. Eighty tubers were irradiated with doses of 0, 20, 40, 100, 150, 200, 500, 1000, 2000, and 3000 Gy. During each irradiation session, the potato tubers were exposed to electron irradiation from two opposite sides to cover the entire surface of the tubers. During the time of exposure, the charge Q_{exp} (nC) absorbed by the duralumin plate, the beam current I (μA), and the irradiation time t (s) were recorded to estimate the dose absorbed by potato tubers (Figure 1b).

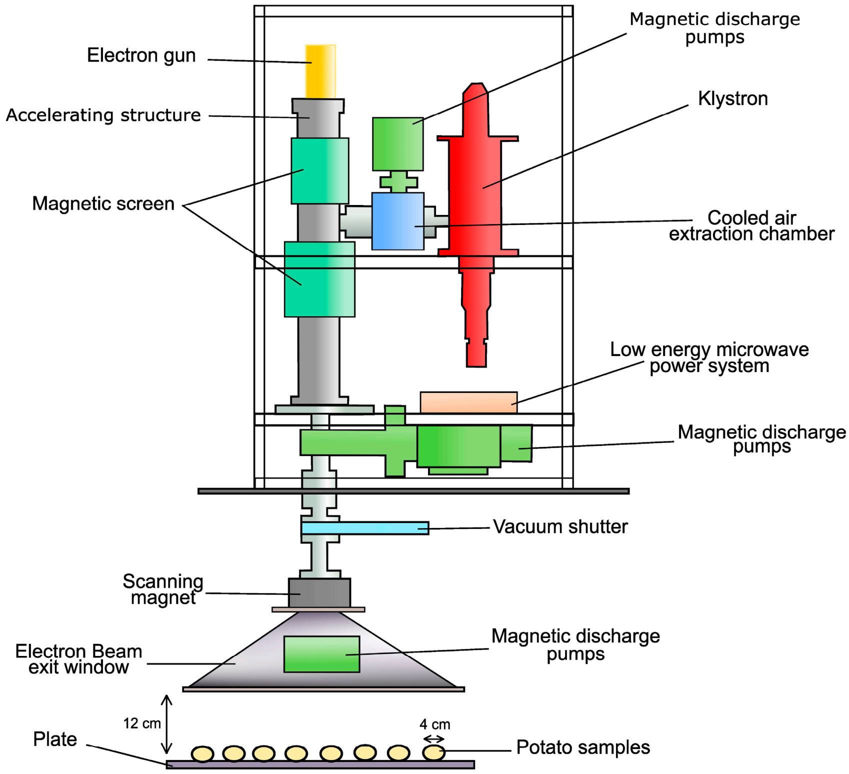


Figure 2. UELR-1-25-T-001 electron beam irradiation method.

2.4. Dose Absorbed by Potato Tubers

To determine the dose absorbed by potato tubers during the irradiation session, it was necessary to determine the electron charge Q_{tubers} absorbed by the tubers. The charge Q_{exp}, which was absorbed by the area of the duralumin S_{plate} free from the tubers and measured using an analog-to-digital converter (OOO Industrial Association "Oven", Moscow, Russia), was also factored in the calculations to estimate Q_{tuber} by the following formulas:

$$\begin{cases} Q_{total} = Q_{exp} + Q_{tubers} \\ \frac{Q_{exp}}{Q_{tubers}} = \frac{S_{plate}}{nS_{tuber}} \end{cases} \Leftrightarrow \begin{cases} Q_{exp} = Q_{total} - Q_{tubers} \\ Q_{exp} = \frac{S_{plate}}{nS_{tuber}} \cdot Q_{tubers} \end{cases} \Rightarrow Q_{tuber} = \frac{S_{tuber}}{S_{plate} - nS_{tuber}} \cdot Q_{exp} \quad (1)$$

where Q_{total} is the charge released by the accelerator, Q_{tubers} is the charge absorbed by all tubers, S_{tuber} is the shadow of one tuber, and n is the number of tubers. The margin error in determining the charge Q_{exp} absorbed by the plate did not exceed 1%.

The tuber was represented by a water sphere with a radius of 20 mm. Since the potato tubers were irradiated from two opposite sides, the water phantom was made of two hemispheres, and the total dose absorbed by the phantom was a sum of the doses absorbed by each hemisphere. It was supposed that the 1 MeV electron beam penetrates the hemisphere perpendicularly to its surface. The fluence of electrons, i.e., the number of electrons N_e falling per unit area of the hemisphere, is equal to $F = N_e \cdot S^{-1} = Q_{tuber} \cdot \left(2\pi R^2 e\right)^{-1}$, where S is the surface area of the hemisphere, $Q_{tuber} = n^{-1} S_{tuber} \cdot \left(S_{plate} - n\, S_{tuber}\right)^{-1} I\Delta t$ is the total charge of electrons, absorbed by one tuber during irradiation, I is the average beam current, Δt is the time of exposure, n = 8 is the number of tubers, and e is the elementary electron charge.

The Cartesian coordinate system should be applied in such a way that its origin coincides with the center of the hemisphere. Thus, the thickness of the hemisphere layer at the distance from the origin of coordinates $r = \sqrt{x^2 + y^2}$ will be equal to $l = \sqrt{R^2 - r^2} = R\sqrt{1 - r^2 \cdot R^{-2}}$ and the number of electrons falling on the ring with the radius r and thickness dr will be equal to $F \cdot 2\pi r dr$.

Assuming that an electron loses energy $E(E_0, l)$ when it passes through a water layer with the thickness l without scattering in the medium, the energy E_{dep} releasing in the hemisphere will be estimated as follows:

$$E_{dep} = \int_0^R FE\left(E_0, R\sqrt{1 - \left(\frac{r}{R}\right)^2}\right) 2\pi r dr. \quad (2)$$

Assuming that the energy loss of electrons is in direct proportion to the electron path, the energy loss ΔE during the path l can be described by the formula:

$$\Delta E = \left[\begin{array}{l} E_0,\ l \geq S_{max}, \\ \frac{E_0 l}{S_{max}},\ l < S_{max}. \end{array} \right. \quad (3)$$

where S_{max} is the maximum range of electrons in the water. The maximum range of 1 MeV electrons is approximately 5 mm, which is less than the radius R of the water sphere. Thus, the Formula (2) transforms to the following form, taking into account Formula (3):

$$E_{dep} = \int_0^{R\sqrt{1-\left(\frac{S_{max}}{R}\right)^2}} FE_0 2\pi r dr + \int_{R\sqrt{1-\left(\frac{S_{max}}{R}\right)^2}}^{R} FE_0 \frac{R\sqrt{1 - \left(\frac{r}{R}\right)^2}}{S_{max}} 2\pi r dr. \quad (4)$$

Therefore, the energy absorbed by the water hemisphere is equal to

$$E_{dep} = FE_0 \frac{\pi}{3}\left(3R^2 - S_{max}^2\right) \quad (5)$$

and the average dose absorbed by the tuber during unilateral irradiation is

$$D = \frac{E_{dep}}{m} = \frac{FE_0 \frac{\pi}{3}\left(3R^2 - S_{max}^2\right)}{\frac{2}{3}\pi R^3 \rho} = \frac{FE_0\left(3R^2 - S_{max}^2\right)}{2R^3\rho} = \frac{E_0\left(3R^2 - S_{max}^2\right)}{4\pi R^5 \rho e} \frac{1}{n} \frac{S_{tuber}}{S_{plate} - S_{tuber}} I\Delta t, \quad (6)$$

where m is the mass of the hemisphere and ρ is the density of water.

2.5. Computer Simulation to Determine the Absorbed Dose Uniformity

The doses absorbed by the tubers and the dose distribution in the tuber were determined using the Monte Carlo method with the help of the toolkit GEANT 4 (CERN, Geneva, Switzerland) [39].

The tuber represented by a Ø 40 mm water sphere was irradiated with 10^8 electrons whose energy was distributed on the UELR-1-25-T-001 electron beam spectrum [35] according to the irradiation method shown in Figure 2a. A 40 mm water cube that contained the water sphere was divided into 40 × 40 × 40 cubic cells with an edge of 1 mm to calculate the dose distribution in the water sphere. For each cell, the total energy ΔE_i obtained through interactions was calculated using the formula $D_i = \Delta E_i \cdot m_i{}^{-1}$, where Δm_i is the mass of the cell. The margin of error for the dose absorbed by the water sphere during the simulation did not exceed 2%.

Table 1 shows the electron charge Q_{exp} absorbed by the duralumin plate free from potato tubers, the exposure time t for bilateral irradiation, and the average electron beam current for each irradiation session.

Table 1. Potato tubers irradiation parameters with 95% confidence intervals.

No.	t (s)	I (μA)	Q (nC)	D_{calc} (Gy)	D_{Geant} (Gy)
1	32 ± 1	0.10 ± 0.01	2070 ± 40/2070 ± 40	20.4 ± 0.4	20.7 ± 0.4
2	50 ± 1	0.10 ± 0.01	4120 ± 70/4080 ± 70	40 ± 1	41 ± 1
3	100 ± 1	0.10 ± 0.01	10,170 ± 200/10,240 ± 200	100 ± 2	102 ± 2
4	150 ± 1	0.10 ± 0.01	15,430 ± 310/15,220 ± 300	150 ± 3	154 ± 3
5	200 ± 1	0.10 ± 0.01	20,320 ± 400/20,360 ± 410	200 ± 4	203 ± 4
6	230 ± 1	1.90 ± 0.01	50,850 ± 1010/50,870 ± 1020	500 ± 10	509 ± 11
7	210 ± 1	4.80 ± 0.01	101,760 ± 2040/101,790 ± 2040	1000 ± 20	1018 ± 20
8	422 ± 1	4.80 ± 0.01	203,300 ± 4070/203,280 ± 4070	2000 ± 40	2033 ± 41
9	632 ± 1	4.80 ± 0.01	305,280 ± 6110/305,310 ± 6110	3000 ± 60	3053 ± 61

Table 1 also presents the doses absorbed by the samples, calculated both using Formula (6) D_{calc} and the computer simulation D_{Geant}. As can be seen from Table 1, the data obtained in these two ways varied by no more than 2%.

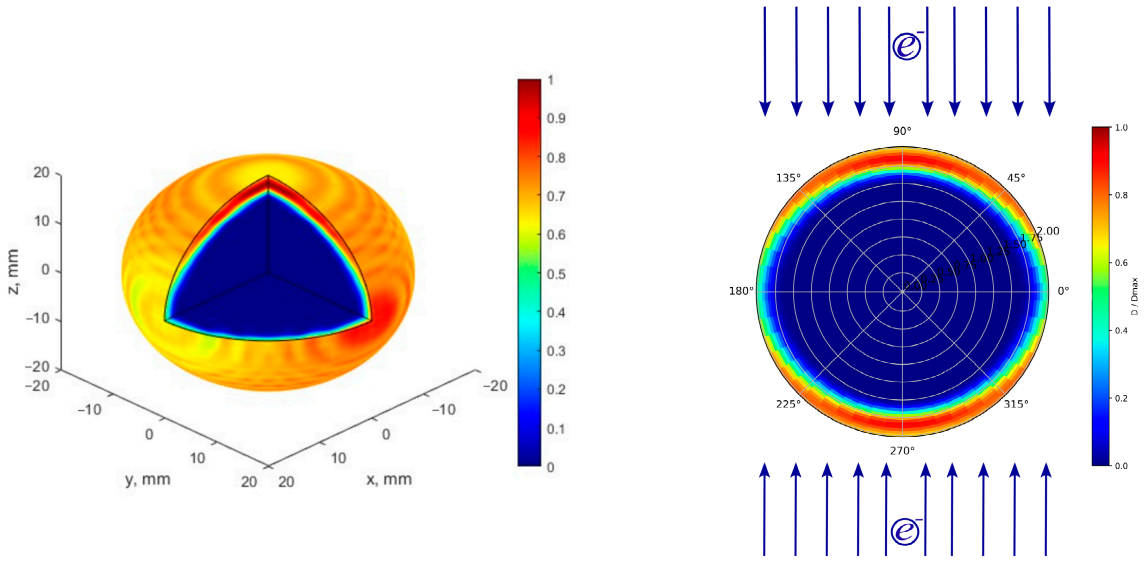
During computer simulation, the dose absorbed by the water sphere was color-coded, and each cell was marked with the color corresponding to the value D_i^{rel}, which is the ratio between D_i and the maximum dose value in the water phantom. The cells of the cube which were not fully filled with water are not represented on the map.

To calculate the dose uniformity in the surface layer of tubers infected with *Rhizoctinia*, a 2D color map of absorbed dose distribution in the central section of the water phantom located in the plane parallel to the initial direction of electrons during its bilateral irradiation was simulated using GEANT 4. The central cross-section of the water phantom was represented by a Ø 40 mm and 0.78 mm thick disk, which was divided into 51 cells along the radius at 0.39 mm increments and 51 cells along the azimuthal angle at 7.05° increments. For each cell, the total energy ΔE_j obtained through interactions was calculated using the formula $D_j = \Delta E_j \cdot m_j{}^{-1}$, where Δm_j is the mass of the cell. The dose absorbed by the water disk was color-coded, and each cell was marked with the color corresponding to the value D_j^{rel}, which is the ratio between D_j and the maximum dose value in the water disk. According to the simulation, the dose uniformity within 2 mm from the surface of the tuber did not exceed 50%.

The whole dose was absorbed in the water sphere surface layers, no deeper than 4 mm (Figure 3a,b). Thus, the interior layers of the potato were not exposed to irradiation. According to the simulation, the dose uniformity within 2 mm from the surface of the tuber did not exceed 50% (Figure 3b).

2.6. Field Study

The experiments were carried out in the open field at the agricultural experimental station of OS Elitnaya located in the forest-steppe Priobsky region in the vicinity of Novosibirsk (Figure 1c). The area where potato tubers were planted is a slightly undulating plain with well-defined microdepressions. The soil of the field is medium-thick leached chernozem of medium loamy granulometric composition with a thickness of the humus horizon of 39 cm. The soil density varied from 1.02 g·cm^{-3} to 1.46 g·cm^{-3} in the plow layer. The density of the solid phase ranged from 2.4 to 2.5 g·cm^{-3}. Throughout a 1-m-deep layer of soil, the wilting moisture was within 109 mm, the lowest moisture capacity was 195 mm, and the total moisture capacity was 370 mm. The content of humus in the plow horizon was 4.2–4.8%, total nitrogen was 0.27–0.41%, phosphorus was 18.0–18.5 mg·(100 g)$^{-1}$, potassium was 7.0–7.7 mg·(100 g)$^{-1}$ of soil, and pH = 6.7–6.8.



(**a**) (**b**)

Figure 3. (**a**) 3D dose distribution map rationed to the maximum dose in the volume of the water phantom under bilateral irradiation of an accelerated 1 MeV electron beam; (**b**) 2D dose distribution map in the central section of the water phantom under bilateral irradiation.

Planting care included pre-emergence harrowing, inter-row tillage, hilling, and vegetation treatment against pests and weeds. Before harvesting, the desiccation of aboveground parts of plants was carried out.

After planting the tubers, the research team registered the germination, budding, and flowering rates of plants grown from irradiated and non-irradiated seed tubers. The germination *G*, budding *B*, and flowering *F* rates were estimated using the following formulas:

$$G = \frac{N_G}{N_{total}}, \tag{7}$$

$$B = \frac{N_B}{N_{Gtotal}}, \tag{8}$$

$$F = \frac{N_F}{N_{Gtotal}}, \tag{9}$$

where N_G is the number of germinated plants, N_B is the number of plants with buds, N_F is the number of plants with flowers, N_{total} is the total number of plants studied, N_{Gtotal} is the number of plants that had germinated by the time the observation started.

The study included the examination of plant phenology and the productivity of potato tubers after pre-planting processing with low-energy electrons (Figure 1d). The new crop tubers were divided into three groups by weight: tubers weighing more than 80 g were attributed to the large fraction, tubers weighing from 40 to 80 g were referred to as the medium fraction, and those weighing less than 40 g were classified as the small fraction.

All new crop tubers grown from irradiated and non-irradiated seed tubers were subjected to a detailed study to differentiate between sclerotia and non-sclerotia diseases caused by of *Rhizoctonia solani*. To assess the extent to which the tubers were infected with *Rhizoctonia sclerotia*, 1/10, 1/4, and 1/2 of the surface of the tubers were examined immediately after harvesting. After classifying the tubers for sclerotia form, each tuber was tested for non-sclerotia forms, such as net necrosis, dented spotting, deformity, and cracks.

3. Results and Discussion

3.1. The Development of Plant Phases

The data obtained during the experiment revealed the non-linear dependency of potato plant biometric parameters on the dose absorbed by seed potatoes during pre-planting processing with accelerated electrons.

Figure 4 illustrates how the pre-planting dose influences the kinetics of the germination (a), budding (b), and flowering (c) of non-irradiated samples, used as controls, and irradiated samples over time. While for control samples and samples irradiated with the doses of 20 Gy and 40 Gy all three phases of plant growth were observed, when the doses of 100 and 150 Gy were applied the flowering phase did not occur, as can be seen from Figure 4c.

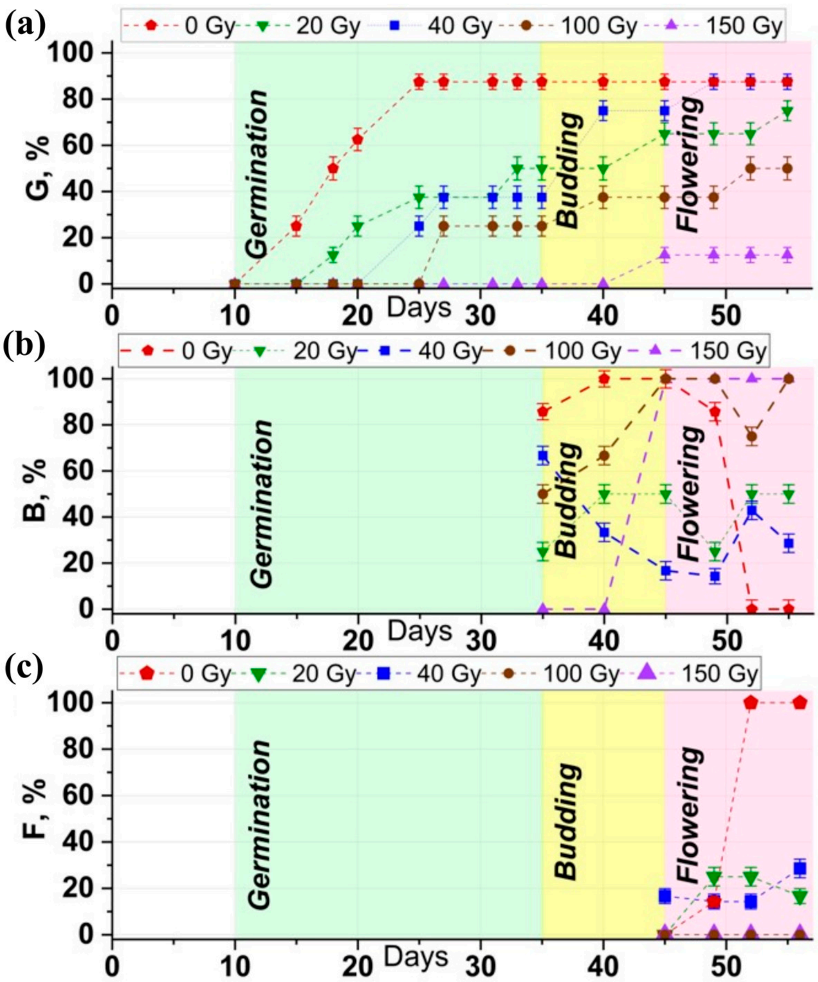


Figure 4. The development of plant germination (**a**), budding (**b**), and flowering (**c**) over time after pre-planting processing of seed potatoes with the doses 0 Gy, 20 Gy, 40 Gy, 100 Gy, and 150 Gy. Green, yellow, and pink zones represent the germination, budding, and flowering phases, respectively.

The germination of 25% of plants grown from control potatoes started on the 15th day after planting (Figure 4a). Irradiated potato seedlings took longer to emerge than non-irradiated control samples. For all stages of plant growth, a more significant delay in potato germination was seen with an increase in the irradiation dose (Figure 5).

Figure 5. Potato plants grown from non-irradiated and irradiated seed potatoes.

When the planting material was irradiated with 20 Gy, the beginning of germination of 25% of seedlings was observed 5 days later than in the control samples. With higher doses applied, namely 40 Gy and 100 Gy, 25% of potatoes started germinating 10 and 12 days later than the control samples, respectively. When potatoes were irradiated with the dose of 150 Gy, the number of samples that sprouted 30 days after the control samples did not exceed 12% of those planted. While the germination phase of 75% of plants grown from non-irradiated potatoes started 22 days after planting, the same share of plants grown from potatoes irradiated with 20 Gy and 40 Gy germinated 55 and 40 days after planting, respectively. To compare, the share of potatoes that germinated after being irradiated with 100 Gy amounted to only 50% of the seedlings. The exposure of planting material to accelerated electrons at 150 Gy did not allow plants to reach the 25% mark.

The tendency of irradiated potatoes to lag behind in development persisted even during the potato budding phase. The time between the phases of germination and budding in the control samples was shorter than in irradiated plants (Figure 4b). For control samples and the samples irradiated with 20 Gy, the 49th day following planting marked the beginning of the flowering phase.

For potato tubers treated with 40 Gy, the flowering phase began 4 days earlier than in the control samples (Figure 4c). Further monitoring showed that 100% of plants grown from control tubers entered the flowering phase on day 52. Almost 30% of plants that sprouted from seed material irradiated with doses of 20 and 40 Gy entered the flowering phase on day 56. With a further increase in the dose applied to seed potatoes, no seedlings entered the flowering phase.

Analysis of plant biometry showed that the kinetics of germination $G(t)$ of control plants and plants whose seed tubers were irradiated with accelerated electrons can be described as a function:

$$G(t) = \frac{G_{max}}{2}\left(1 + \frac{2}{\sqrt{\pi}}\int_0^{\frac{t-t_0}{\Delta\sqrt{2}}} e^{-x^2}dx\right), \quad (10)$$

where G_{max} is the maximum value of G parameter, t_0 is the time by which half of the plants germinated, Δ is the standard deviation of the t_0 value.

Figure 6 shows the germination of irradiated and control potato tubers and the functions approximated by experimental data described by Formula (7). The parameters of Formula (7) were estimated by the Levenberg–Marquardt algorithm for different doses and are presented in Table 2.

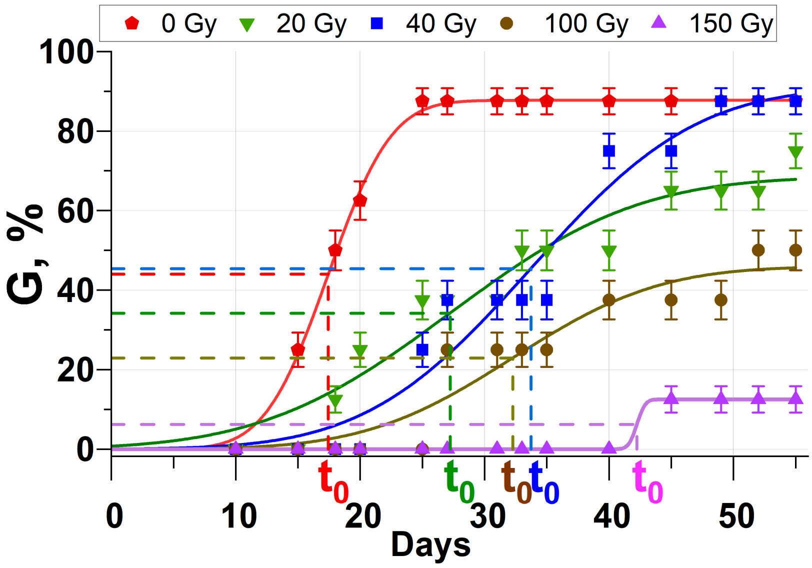


Figure 6. Germination kinetics of potatoes treated with different doses and functions approximated with experimental data using Formula (7) shown as solid lines.

Table 2. Parameters of function (7) describing the germination of irradiated and control potato tubers with 95% confidence intervals.

Dose (Gy)	**Parameters of $G(t)$ Function**			**R**
	t_0 (Days)	**Δ (Days)**	**G_{max} (%)**	
0	17.4 ± 0.2	3.99 ± 0.40	87.7 ± 1.0	0.99
20	27.2 ± 3.7	11.9 ± 5.0	68.5 ± 9.9	0.97
40	33.7 ± 3.8	10.4 ± 4.6	90.9 ± 15.6	0.98
100	32.3 ± 4.5	9.3 ± 6.0	45.9 ± 9.6	0.96
150	42.2 ± 3.9	0.5 ± 0.9	12.5 ± 6.0	0.99

Table 2 shows that while the standard deviation Δ for the samples irradiated with 20, 40, and 100 Gy varied from 9 to 12 days, for 150 Gy it was 0.5. The control samples took 8 days to germinate almost 90% of tubers, and the doses of 20 Gy, 40 Gy, and 100 Gy took 2.5–3.5 times longer to reach the maximum value of germination. The correlation coefficients are 0.96–0.99, which indicates the adequacy of the proposed approximation of tuber germination using Formula (10).

3.2. Total Yield and Its Fractional Composition

The germination, budding, and vegetation processes had an impact on crop yield and its fractional composition: the higher the irradiation dose, the lower the crop yield (Figure 7b). Three fractions were identified when determining the fractional composition as follows: small tubers weighing less than 40 g, medium tubers weighing between 40 and 80 g, and large tubers weighing more than 80 g.

Figure 7a shows pie charts representing the fractional composition of crops grown from control and irradiated potatoes. Fractional composition analysis revealed that more small and medium tubers were gained from seed potatoes irradiated with doses ranging from 20 Gy to 100 Gy compared with control samples. The small fraction of potatoes was completely absent after irradiation with 150 Gy; the large fraction predominated over the medium fraction. The crop grown from control potatoes and the potatoes irradiated with 20 Gy is mainly represented by the large fraction, while 40 Gy and 100 Gy yielded more medium fraction than large. It can be noted that the ratio of the small fraction increased from 0.7% to 11% with an increase in the dose from 0 Gy to 100 Gy used for pre-planting processing (Figure 8).

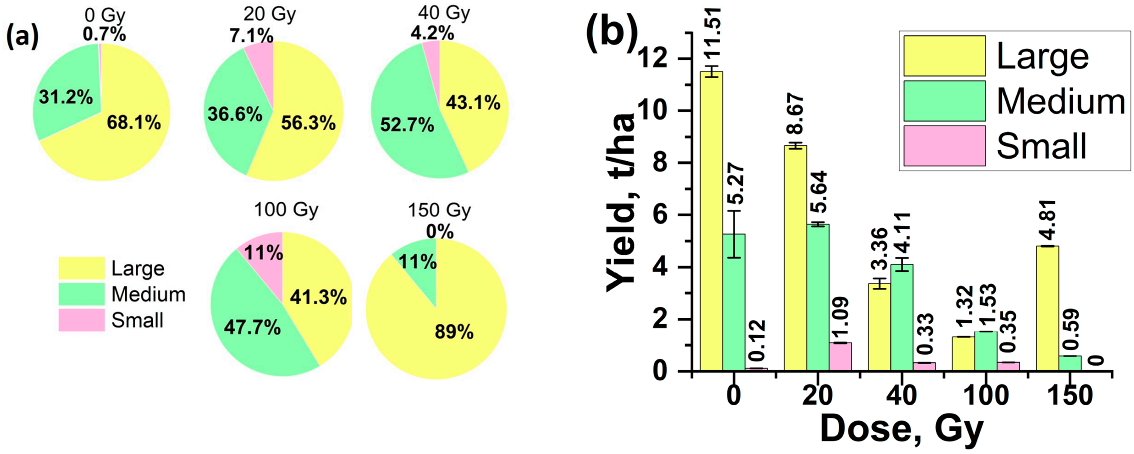


Figure 7. (**a**) Pie charts representing the fractional composition of crop grown from control tubers and from tubers irradiated with 20 Gy, 40 Gy, 100 Gy, and 150 Gy; (**b**) Total crop yield distribution and its fractional composition.

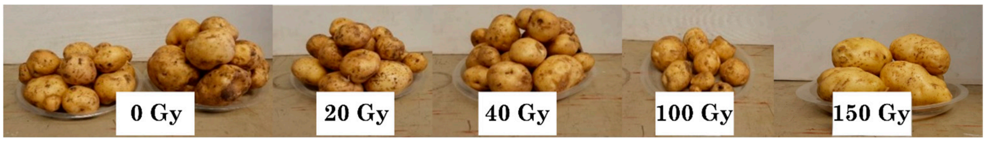


Figure 8. The new crop grown from non-irradiated and irradiated seed potatoes.

Figure 7b shows the crop yield grown from control seed material and from seed tubers irradiated with different doses. As can be seen, the amount of crop yield reduced with an increase in the dose of pre-planting processing.

3.3. The Rate of Phytopathogenic Diseases of the New Crop

The crop grown from irradiated and non-irradiated tubers was analyzed to determine both non-sclerotia and sclerotia diseases in tubers caused by *Rhizoctonia* (Table 3).

Table 3. *Rhizoctonia* diseases found in control tubers and tubers grown from irradiated seed material with 95% confidence intervals.

***Rhizoctonia* Forms**	**Dose (Gy)**				
	0	**20**	**40**	**100**	**150**
Non-sclerotia diseases					
Net necrosis	98 ± 9	100 ± 9	88 ± 7	70 ± 7	67 ± 7
Dented spotting	91 ± 9	18 ± 3	19 ± 2	ND [1]	ND
Cracks	13 ± 9	12 ± 2	6 ± 1	10 ± 2	ND
Deformity	2.2 ± 0.4	12 ± 2	ND	ND	ND
Sclerotia disease					
R. solani	100 ± 9	100 ± 9	56 ± 6	10 ± 2	ND

[1] Not Detected.

Table 3 shows that net necrosis, which predominated among non-sclerotia diseases in crops, declined nonlinearly with an increase in irradiation dose of pre-planting processing. Dented spotting was registered in all experimental samples, except those irradiated with 100 Gy and 150 Gy. Interestingly, potatoes grown from control samples contained the highest number of dented spots among all the samples studied during the experiment. Both in control samples and samples grown from seed material irradiated with 20 Gy and 100 Gy, cracks occur in 12–13%. The deformity of new crop tubers which appeared after irradiation of planting material with 20 Gy exceeded the deformity of control samples by almost 10%.

A recent investigation [35] has shown that when *Rhizoctonia solani* sclerotia, separated from the potato tuber, was exposed to electron irradiation with doses ranging from 20 Gy to 900 Gy, no discernible impact on their growth was observed. A further increase in the dose lowered the mycelium growth rate while the doses above 4500 Gy completely inhibited the development of the fungus during the entire observation period.

It can be noted that all tubers grown from irradiated samples and control samples had sclerotia diseases, while tubers grown from seed material irradiated with 150 Gy had no sign of *Rhizoctonia solani*. Irradiation of planting material with the doses of 40 Gy and 100 Gy visibly reduced the spread of sclerotia on new crop tubers, which was more evident with a higher dose. Since sclerotia diseases caused by *Rhizoctonia* occur on the surface of potatoes, 1 MeV electrons which penetrate the tubers no deeper than 5 mm from the surface level can be seen as an effective method of suppressing sclerotia forms.

3.4. Preliminary Results

During the research, it was found that pre-planting irradiation of potato seed tubers with a dose ranging from 20 Gy to 150 Gy delayed the development of emerging plants, and the dose exceeding 150 Gy completely inhibited germination. With an increase in the irradiation dose, the germination, budding, and flowering started later than in control potato samples. Moreover, with a higher dose, the germination rate decreased compared to the control samples. Both control and irradiated samples showed a sigmoid growth of germination with an increase in time after the planting of seed material. Control plants and plants grown from the seed tubers exposed to 40 Gy reached the maximum germination rate of 90%, while other samples grown from the seed material irradiated with 20 Gy, 100 Gy, and 150 Gy reached a lower germination rate compared to the control samples. Moreover, with an increase in the irradiation dose, the germination rate of irradiated samples decreased.

It was found that the new crop yield decreased with an increase in the irradiation dose of seed potatoes; although with a higher dose, the percentage of tubers infected with *Rhizoctonia solani* in the new crop decreased compared to control samples. The pre-planting irradiation of seed material also influenced the fractional composition of the new crop tubers. It was evident that more small and medium tubers were gained from seed potatoes irradiated with the doses ranging from 20 Gy to 100 Gy compared with the control samples.

3.5. Comparison Study

Potato irradiation research carried out globally is predominantly aimed at finding the radiation doses for potatoes that would extend potato shelf life and much less research focuses on pre-planting irradiation treatment of seed material to enhance the quality of new crops and the ways it is difficult to secure the reduction in the amount of phytopathogens in tubers without causing a negative impact on the growth and yield of seed material.

Recent research [40] shows that gamma irradiation with 20 Gy is able to increase potato growth rate, doses above 20 Gy suppress potato germination, and doses above 60 Gy completely inhibit potato growth. Our research does not provide evidence for a stimulating effect of low-energy electron irradiation with the dose of 20 Gy; however, irradiation with 20 Gy has no significant impact on plant germination and crop yield, and doses above 100 Gy significantly reduce the growth rate and the seed potato yield.

The research [28] carried out at the Experimental Farm of Baloza station, Desert Research Center, North Sinai confirms that 20 Gy gamma irradiation in combination with 80% irrigation increases the average tuber weight and total potato yield. In contrast, research [41] proves that gamma irradiation ranging from 15 Gy to 50 Gy reduces the total yield, which is consistent with our findings obtained during the research. Our research shows that pre-planting irradiation with 150 Gy increases the average weight of tubers while decreasing the total yield.

Recent research [42] showed that gamma irradiation with 5–10 Gy increases the number, weight, and size of microtubers, which are frequently used in studies presently.

Considering that minitubers and microtubers are increasingly used in agriculture, it would be interesting to explore the impact of pre-planting electron irradiation on these kinds of potato tubers.

3.6. Effective Dose Range for Pre-Planting Processing of Seed Tubers

The impact of irradiation on the seed material can be explained by the physics of the interaction of electrons with biological objects. Accelerated electrons lose energy when they directly interact with the atomic electrons of meristem cell structures of tuber seedlings, leading to single- and double-stranded DNA breaks and the destruction of the cell membrane. Moreover, reactive oxygen species appearing as a result of the radiolysis of water contained in the tubers break chemical bonds in cell molecules, causing the inactivation of meristem cells. Thus, exposure to radiation inhibits tuber germination, and the higher the dose, the more inactivated cells appear after irradiation. Since *Rhizoctonia solani* sclerotia can be found on the surface of tubers, low-energy electrons penetrating the surface layers of the tubers damage sclerotia cells, and, consequently, decrease seed tuber infection rate. Therefore, the effect of radiation on plant development and phytosanitary conditions is achieved by the direct and indirect impact of irradiation on the biological structures of the infected seed tubers.

Based on the experimental data, it can be assumed that seed potato tubers represent two statistical ensembles, each of whom is characterized by a different dose that decreases the crop yield (Figure 9). This can be explained by the fact that each tuber has a shape of an ellipsoid, and the axillary buds located on the tuber surface, which is perpendicular to the initial direction of electrons, were exposed to a different dose to compare with the axillary buds on the sides of the tubers (Figure 3b). At the same time, the distribution of axillary buds on the surface and their depth are different for each tuber. Each axillary bud requires a certain number of ionization events to curb sprouting. Therefore, axillary buds located close to the surface on the pathway of electrons require a lesser dose to curb sprouting compared to those located deeper on the lateral surface of the tuber. The biological effect on seed potatoes from accelerated electrons can be influenced by the quantity of ionization events per one square centimeter of the tuber surface, as well as the position of axillary buds on the tuber surface and the dose uniformity over the tuber surface (Figure 3a,b).

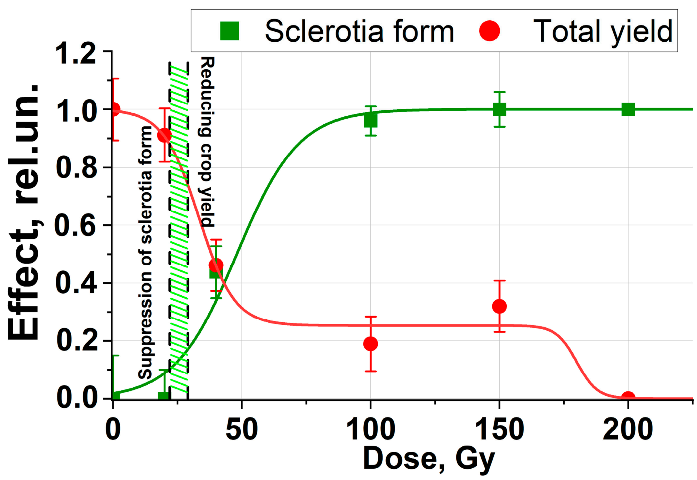


Figure 9. Dependencies of the total yield of potatoes, the yield represented by the middle fraction, and the prevalence of sclerotia and non-sclerotia diseases caused by *Rhizoctonia* on tubers of a new crop on the dose of irradiation of planting material growth.

At the same time, seed tubers represent one statistical ensemble in terms of inhibiting sclerotia disease by means of radiation. This can be explained by the fact that the dose distribution created by 1 MeV electrons has the maximum value at a distance not exceeding 1 mm (Figure 3b). Since sclerotia are located on the surface of the tuber, a low-energy electron beam that ensures a maximum dose in the surface layers of the tuber can efficiently inhibit sclerotia disease caused by *Rhizoctonia*.

Figure 9 shows the dependency of the yield y relative to control parameters in new crop tubers on the dose D applied to the seed potatoes. The dependency $Y(D)$ can be approximated using the following formula:

$$Y(D) = \frac{y_{max1}}{1 + \exp\left\{\Delta_1\left(D - \widetilde{D_1}\right)\right\}} + \frac{y_{max2}}{1 + \exp\left\{\Delta_2\left(D - \widetilde{D_2}\right)\right\}}, \quad (11)$$

taking into account that $y_{max1} + y_{max2} = 1$, where y_{max1} is the maximum value of the yield grown from the first statistical ensemble of seed potatoes; $\widetilde{D_1}$ is the dose at which the total yield grown from the first statistical ensemble decreases two times compared to the control samples; Δ_1 is the rate parameter of the first statistical ensemble; $\widetilde{D_2}$ is the dose at which the total yield grown from the second statistical ensemble decreases two times compared to the control samples; Δ_2 is the rate parameter of the second statistical ensemble.

Figure 9 also shows the dependency of the prevalence of sclerotia disease S relative to the control parameter in new crop tubers on the dose D applied to the seed potatoes.

$$S(D) = 1 - \frac{1}{1 + \exp\left\{\Delta_3\left(D - \widetilde{D_3}\right)\right\}}, \quad (12)$$

where $\widetilde{D_3}$ is the dose at which the prevalence of sclerotia disease was suppressed two times compared to the control samples; Δ_3 is the rate parameter of $S(D)$ dependency. The parameters of Formulas (11) and (12) are presented in Table 4. The parameters were estimated by the Levenberg–Marquardt algorithm.

Table 4. Parameters of functions (11) and (12) describing the dependencies of the yield Y and the prevalence of sclerotia disease S on the dose D with 95% confidence intervals.

Parameters of Y(D) Dependency						
y_{max1} (rel.un.)	$\widetilde{D_1}$ (Gy)	Δ_1 (Gy^{-1})	y_{max2} (rel.un.)	$\widetilde{D_2}$ (Gy)	Δ_2 (Gy^{-1})	R
0.74 ± 0.09	33 ± 4	0.148 ± 0.06	0.26 ± 0.09	172 ± 15.6	0.85 ± 0.07	0.99
Parameters of S(D) Dependency						
$\widetilde{D_3}$ (Gy)			Δ_3 (Gy^{-1})			R
43 ± 3			0.112 ± 0.013			0.99

The correlation coefficients are 0.99, which indicates the adequacy of the proposed approximation of $Y(D)$ and $S(D)$ dependencies using Formulas (11) and (12).

It can be concluded that each tuber is characterized by a certain threshold value of the dose $\widetilde{D}$, after which it stops producing crops. This means that if a seed potato is irradiated with a dose above $\widetilde{D}$ it will not produce any yield. The value $\widetilde{D}$ depends on many factors, such as the variety of the tubers, chemical composition, vitamin content, the presence of fungal, viral, and bacterial diseases, and the temperature and humidity.

Low-energy electrons used for the suppression of phytopathogens have proved to be efficient for pre-planting irradiation of seed potatoes since they penetrate the surface layer without affecting the internal structure of the tubers. This approach is appropriate since sclerotia diseases caused by *Rhizoctonia solani* can be found in the 2 mm surface layer of potato tubers. However, it is important to maintain a reasonable balance to ensure that the suppression of fungal diseases does not compromise the quantity of crop yield. The irradiation dose range should, on the one hand, be sufficient for the suppression of pathogens, and, on the other hand, should not inhibit potato growth that would cause the crop yield to drop below the economically feasible level. Thus, for the practical implementation of low-energy electrons, it is recommended to establish effective lower and upper dose range limits to ensure the suppression of sclerotia diseases caused by *Rhizoctonia solani* by at least

10% from the value of non-irradiated samples infected with *Rhizoctonia solani*, allowing for a maximum of 25% of potato yield loss.

During the research, it was established that pre-planting 1 MeV electron irradiation of seed potatoes with doses ranging from (20 ± 2) Gy to (28 ± 2) Gy is effective for enhancing the quality of the new crop yield since it suppresses sclerotia diseases as specified above without dramatically reducing the potato yield.

4. Conclusions

Considering the current trend in favor of electron accelerators for industrial irradiation due to a higher processing speed compared with gamma sources, the development of food irradiation methods that use accelerated electrons has become a priority for researchers in Russia. As crop safety and security has become a pivotal point for ensuring the sustainable growth of the agricultural industry, it is important to develop the most effective approach to the pre-planting treatment of seed material depending on the type, genus, and geometry of the crop, considering that a one-size-fits-all-approach is unable to mitigate the damage to the crop yield caused by various fungal diseases.

While globally gamma irradiation is predominantly used for the irradiation of crops, our research focuses on implementing electron irradiation in the agricultural industry. Since the electron accelerators allow the variation of the energy of electrons, it is possible to control the penetration depth of electrons in crops in a targeted manner. This study explores the impact of low-energy accelerated electrons on the suppression of phytopathogens, which affect the surface layer of seed potato tubers, as 1 MeV electrons, used in the study, with a maximum penetration depth of 5 mm have proved to be efficient for the pre-planting irradiation of seed potatoes. In the absence of any data on pre-planting irradiation of seed material infected with phytopathogens using low-energy electrons, it can be assumed that the irradiation method proposed in the study is a novelty in the field of agriculture.

During the research, it was established that pre-planting 1 MeV electron irradiation of seed potatoes with doses ranging from 20 Gy to 30 Gy is effective for enhancing the quality of the new crop yield since it suppresses sclerotia diseases as specified above without dramatically reducing the potato yield.

In the future, we plan to study sclerotia on seed potato tubers after irradiation in order to assess the impact of accelerated electrons on the phytopathogen directly on the tuber at the time of irradiation. Additionally, it is of interest to study potato photosynthesis after exposure to electrons.

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