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Method for the Reduction of Natural Losses of Potato Tubers During their Long-Term Storage

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Abstract: The purpose of the study was to establish whether UV-C radiation applied to potato tubers prior to their storage affected their natural losses over a long period of time. A custom-built UV-C radiation stand constructed for the purpose of this experiment was equipped with a UV-C NBV15 radiator generating a 253.7 nm long wave with power density of 80 to 100 $\mu W \cdot cm^{-2}$. Three varieties of edible medium late potatoes, Jelly, Syrena, and Fianna, were the objects of the research. The measurement of tightly controlled storage conditions was carried out over three seasons between 2016/2017 and 2018/2019, in a professional agricultural cold store with automated adjustment of interior microclimate parameters. The obtained data were processed using the variance analysis ($\alpha = 0.05$). There was a statistically significant reduction in transpiration- and respiration-caused losses in the UV-C radiated potato tubers in comparison to those of the control sample. Additionally, the Jelly variety reacted to UV-C radiation demonstrating a reduction in sprout weight.

Keywords: potato; tuber; storage losses; UV-C

1. Introduction

The biological effects of UV-C (ultraviolet light) on the preservation of fresh fruits and vegetables is well researched. Treatment with UV-C radiation is one of the methods used to reduce the number of pathogens on the surface of fresh fruits and vegetables [1]. It can be an alternative to other traditional methods, such as disinfectants (chlorine, chlorine dioxide, bromine, iodine, trisodium phosphate, sodium chlorite, sodium hypochlorite, quaternary ammonium compounds, acids, hydrogen peroxide, ozone, permanganate salts) [2–5], modified atmosphere packaging [6–11], low temperature storage [11–13], or the use of edible films [14–18]. The alternative methods mentioned above are selective in reducing the number of pathogens on the surface of fresh fruits and vegetables, whereas the UV-C is a nonselective method. UV-C has a germicidal effect, but it is strongly dependent on the natural resistance of the microorganisms to UV-C [19], and the surface topography on which the microorganisms are attached [20]. By delaying the ripening process, the UV-C treatment extends the shelf life of fruits and vegetables [21–24]. A number of studies showed that UV light can be used to control the fungal decay of citrus fruits [25], kumquats [26], carrots [27,28], apples [29], strawberries [30–33], sweet cherries [30], mandarins [34], bell peppers [35], mangos [36,37], blueberries [38], grapes [39], and persimmon fruits [40]. Recent publications also describe similar effects on potatoes. Pristijono et al. [41] describe their preliminary research on the effect of UV-C irradiation on the sprouting of stored potatoes. Rocha et al. [42] present the use of UV-C radiation and fluorescent light to control postharvest soft rot in potato seed tubers. According to Stevens et al. [43] irradiation of potato tubers (*Ipomea batatas* L.) with UV-C increases their resistance to rot caused by *Fusarium solani* fungi.

Long-term storage of potato tuber crop is associated with quantitative changes involving, inter alia, reduction of the original weight of tubers due to respiration, transpiration, and sprouting. These processes, termed tuber weight losses, are unavoidable, but their extent can be minimized. Respiration, transpiration, and sprouting processes are mainly determined by the temperature and relative humidity of air during storage. Meteorological conditions during the vegetation season, genetic characteristics of varieties, and mechanical damage to tubers caused during harvesting and post-harvest treatment may also be responsible for natural losses of the potato tubers [44–49]. Several researchers [50–52] recommend using physical methods to improve crop condition during the storage alongside the biological and chemical methods of protection. Various systems using the UV-C light exposure have appeared in the literature for crops other than potatoes [53,54]. Zhu et al. [53] evaluated the effect of three UV-C wavelengths (222, 254, and 282 nm) on degradation of the mycotoxin patulin introduced into apple juice and apple cider. Falguera et al. [54] investigated the influence of ultraviolet irradiation (UV) on some quality attributes (color, pH, soluble solids content, formol index, total phenolics, sugars, and vitamin C) and enzymatic activities (polyphenol oxidase, peroxidase, and pectinolytic enzymes) of fresh apple juice. Another pilot experiment carried out by Jakubowski [55] analyzed the effect of UV-C radiation on the possible reduction of storage losses caused by transpiration and respiration of potato tubers of the following varieties: Lord, Vineta, Owacja, Ditta, Finezja, and Tajfun. It was assumed that ultraviolet radiation in the C band (253.7 nm) applied to potato tubers before storage would cause a reduction of pests present on the potato periderm. This would indirectly cut down the overall storage losses. It was also assumed that following the exposure of potato tubers to UV-C radiation, the population of pathogens typically present during storage processes would also be limited. This, in turn, could lead to a more effective repair of the periderm damage caused by mechanical harvesting, transport, and initial crop storage. In order to verify the research hypothesis, the tubers of selected varieties were initially mechanically damaged under laboratory conditions, so that the continuity of periderm was broken. An MTS Insight 2 strength testing machine (a device allowing for damage of the potato tuber pulp so that the shape and size of the damage are identical in the tested material regardless of the size, weight, or mechanical properties of the tuber) was used to damage the tubers. The results of the pilot research proved a reduction in the natural loss of potato compared to the control sample across all the used varieties. For Vineta and Ditta, these differences were statistically significant ($\alpha = 0.05$). The experiment described above was conducted over a 5-month storage period, and the tuber weight loss (represented by very early, early, and medium-early varieties) was analyzed only before and after the storage time. It is therefore reasonable to measure the reaction of stored potato tubers to UV-C radiation in subsequent stages during their storage, focusing on the losses caused by respiration and transpiration (particularly after a period of physiological dormancy when the sprouting process begins, which is accompanied by an increased transpiration process).

The purpose of this project was to determine the impact of pre-storage UV-C irradiation of potato tubers on potato tuber natural losses measured over a long period of storage.

2. Materials and Methods

2.1. Potato Tubers

The medium-late varieties of edible potatoes used in the research were Jelly, Syrena, and Fianna. Each tuber went through an identical annual agrotechnical procedure. The tubers for analysis, under the stage of full technical maturity and mechanically undamaged, were randomly selected from the crop commercial fraction ($\Phi = 35$–55 mm). The selection of tubers size was necessary to provide uniform UV-C exposure doses in the research procedure. When determining the minimum sample size, the *t*-test was applied for a single sample (at population mean and standard deviation values from pilot studies), the test target power was assumed to be equal 0.9, and the probability of a type I error $\alpha = 0.05$. Each experiment combination involved three replications (with 30 pcs for single replication).

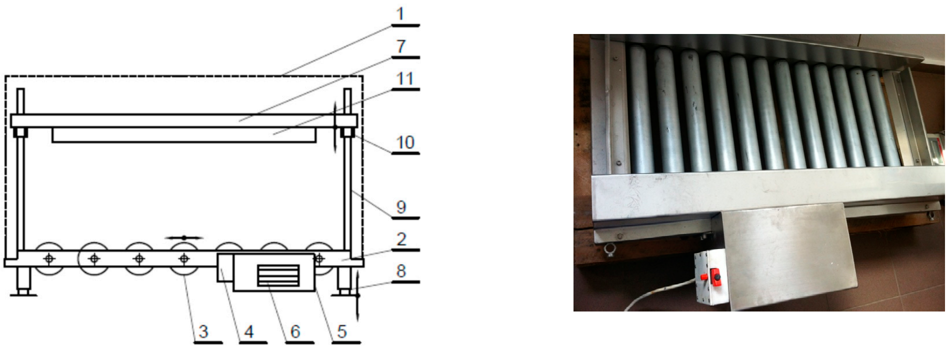
The scope of the research encompassed the measurements of tuber weight losses arising from the processes of respiration, transpiration, and sprouting. The tuber weight was determined before storage (M0), during the initial storage period corresponding to the cooling stage (M1), during the proper storage period (M2), during the first signs of sprouting (M3), and immediately after the storage process (M4). The tuber weight losses were calculated as the difference between M0 and Mn, n = 1–4. Immediately after the storage process, the potato tuber sprout weight and number (Mk, Lk) were also determined.

2.2. Period of Trials and Conditions

Accurate storage experiments were carried out over three seasons between 2016/2017 and 2018/2019 in a professional agricultural cold store with automated adjustment of interior microclimate parameters. After the crop was harvested in the second to third decades of September, the selected tubers underwent weight examination and ultraviolet irradiation in the C band. Then, they were placed in a cold store for initial storage. To standardize the conditions of heat and mass exchange with the environment while storing and to minimize the impact of possible temperature and humidity differentiation, the tubers were stored in wooden cases in single layers and the free spaces between the cases were of similar size. Initial storage lasted for approximately 10 days at a temperature of 15 °C and a relative humidity of 90%–95%. After this period, the storage temperature was gradually reduced to 7 °C. This process took approximately 14 days. The air relative humidity during this period amounted to 92%–95%. From the second to third decades of October to the first decade of March, tubers were stored at a temperature of approximately 7 °C and a relative humidity of 92%–95%. At 10 days before the expected end of the storage period, mid-March, the temperature in the cold chamber was increased to 10 °C.

2.3. Equipment

Potato tuber weight and sprout weight were determined using the AS310.R2 analytical scale (d = 0.1 mg) with the RS232 interface. Potato tubers underwent ultraviolet irradiation (Figure 1) in the C band for 900 s at a constant height of the UV-C radiator (0.7 m) above the surface of the rollers rotating at a constant speed of 25 rpm (exposure time and working parameters of the station were selected based on the results of pilot studies [55]). In order to expose potato tubers to UV-C, the custom-built stand illustrated in Figure 1 was used. A UV-C NBV15 radiator was used (light wave length 253.7 nm, power 15 W, and power density from 80 to 100 $\mu W \cdot cm^{-2}$), equipped with a precise timer (AURATON 100). The lifetime of the NBV15 radiator applied in the research, guaranteeing stability of its operational parameters (UV-C radiation intensity of 0.9 $W \cdot m^{-2}$ at a distance of 1 m from the radiator), is 8000 h. The radiator is equipped with a reflector made of high quality aluminum with a high reflection coefficient (similar to the coefficient of a mirror). The potato tuber radiation stand is equipped with a system of exchangeable, parallel, and sliding rollers acting as the bottom of the chamber. The rollers, with a diameter of 45 to 55 mm, are installed on a rail, and the distances between them range from 15 to 25 mm. They are driven electrically, with rotational speed control ranging from 20 to 35 rpm. The speed range was selected so that the potato tubers placed on the rollers were set in rotation, but at the same time they were not displaced along the chamber, which allowed for equal irradiation of the entire surface of the potato tubers. The presented test stand, together with the technology allowing for limitation of storage losses of potato tubers, was submitted as an invention to the Patent Office of the Republic of Poland (P.419392, P.425887: More details about patents are mentioned below in the Patents section).



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

Figure 1. Stand for potato tubers UV-C radiation: (**a**) stand layout, (**b**) view of rotating rollers. L: 1: chamber housing, 2: device frame, 3: rotating rollers, 4: mechanism for gradeless regulation of roller rotation speed with the device switch, 5: engine, 6: engine cooling system, 7: radiator frame, 8: height-adjustable foot (screw mechanism for leveling the device), 9: radiator frame guide, 10: gradeless UV-C radiator control above the bottom of the chamber (rollers), 11: UV-C radiators.

2.4. Statistical Analysis

The analysis of variance, preceded by the test regarding the distribution normality in the samples (Kolmogorov–Smirnov test) and the variance homogeneity test (Levene's test), was carried out. The zero hypothesis was verified based on the F-Snedecor test. When examining tuber weight data, the variance was analyzed for arrangements with repeated measurements (with Mauchley sphericity test), and for sprouting data, the variance was analyzed for main effects. Due to the biological nature of the examined object, a possibility of a lack of parity in the samples was assumed a priori. Differences between statistically significant averages were examined using the Spjotvoll–Stoline multiple comparison test (generalization of the Tukey procedure for samples with different N). Groups of homogeneous variables were set. In the analysis of data presented in graphical form (Figures 2–4), the Student's t-test was used for related variables. The obtained results were analyzed at the significance level $\alpha = 0.05$ using the STATISTICA 13.3 package.

3. Results

The results of the experiment are presented in Tables 1–3 and in Figures 2–4. Test results from Kolmogorov–Smirnov, Levene, and Mauchley tests allowed for the variance analysis presented in the methodology. The variance analysis proved a significant effect of potato tuber UV-C irradiation before storage on weight loss after storage (predictor: "UV-C exposition {3}", received values: $F = 6.868$; $p = 0.0089$) (Table 1). The variance analysis for arrangements with repeated measurements proved a significant impact of repeated measurement (time: measurement in subsequent storage stages; predictor: "Time {4}", received values: $F = 4498.591$; $p = 0.0000$) and its interaction with other qualitative predictors (predictor: "Time {4} x Variety {2} x UV-C exposition {3}"; received values: $F = 2.329$; $p = 0.0301$) (Table 1). In all the experiment variants, smaller natural losses of potato tuber weight (caused by transpiration and respiration) were observed for the UV-C radiated tubers in comparison to the control sample (Figure 2). Multiple comparisons of average pairs and homogeneous-variables groups determined on this basis (Table 2) showed significant differences in the size of potato tuber natural weight loss (caused by transpiration and respiration) between subsequent storage stages. However, in stages I-III no differences resulting from the variety nor UV-C radiation were shown (letters "a", "b", "c": no statistical differences) (Figure 2). Significant differences in the size of potato tuber natural weight loss (caused by transpiration and respiration) were observed in stage IV for the Jelly variety (3.787 $g \cdot g^{-1}$ for sample Jelly+UV-C and 4.308 $g \cdot g^{-1}$ for control sample; letters "d" and "e") (Table 2). The variance analysis for the impact of the year of the experiment, variety, and UV-C radiation on the weight and number of potato tuber sprouts after the storage period proved a significant impact (Table 3) on the last two quality predictors and their interactions on dependent variables (predictors: Variety {2} x UV-C exposition {3}; F = 5.20; p = 0.0004).

Table 1. Results of the analysis of variance for repeated measurements: Impact of the year of testing, variety, and UV-C irradiation on potato tuber weight loss in individual storage periods.

Qualitive Predictor and Interaction	Sum of Square	Degrees of Freedom	Mean Square	Value of F-Snedecor test	Probability Test
Free Word	38815.53	1	38815.53	5391.355	0.0000
Year {1}	4.98	2	2.49	0.346	0.7078
Variety {2}	22.46	2	11.23	1.560	0.2104
UV-C exposition {3}	49.45	1	49.45	6.868	0.0089
{1}x{2}	55.41	4	13.85	1.924	0.1039
{1}x{3}	11.46	2	5.73	0.796	0.4513
{2}x{3}	12.18	2	6.09	0.846	0.4293
{1}x{2}x{3}	37.48	4	9.37	1.301	0.2673
Error	11533.74	1602	7.20		
Time {4}	8273.54	3	2757.85	4498.591	0.0000
{4}x{1}	0.80	6	0.13	0.217	0.9717
{4}x{2}	6.28	6	1.05	1.706	0.1152
{4}x{3}	23.42	3	7.81	12.732	0.0000
{4}x{1}x{2}	12.45	12	1.04	1.692	0.0618
{4}x{1}x{2}x{3}	1.83	6	0.31	0.498	0.8102
{4}x{2}x{3}	8.57	6	1.43	2.329	0.0301
{4}x{1}x{2}x{3}	13.60	12	1.13	1.849	0.0357
Error	2946.30	4806	0.61		

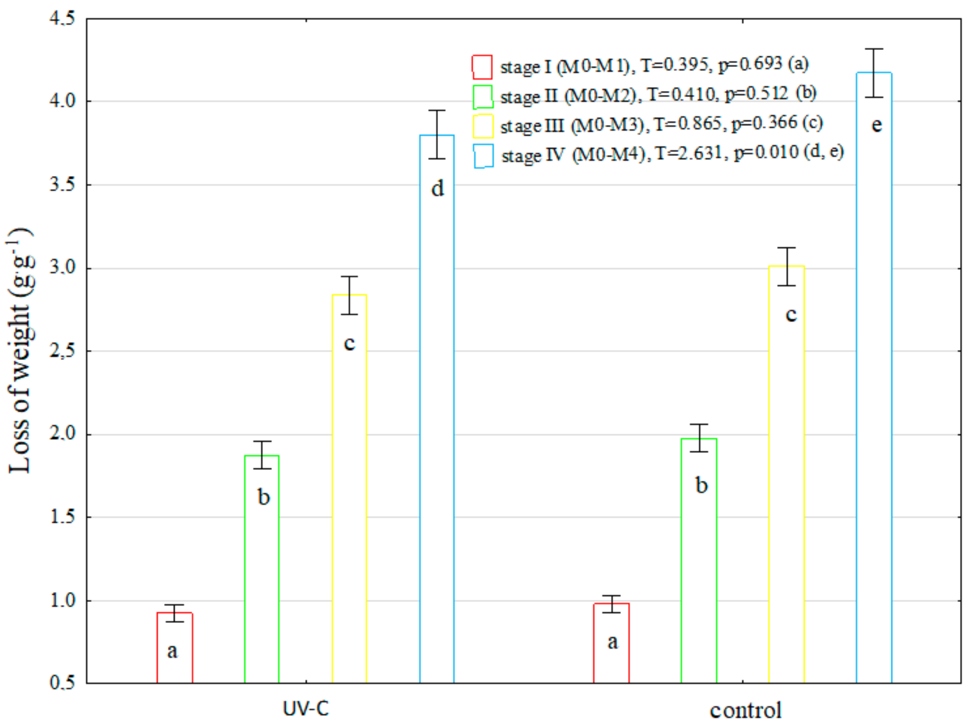


Figure 2. Effect of UV-C irradiation on weight loss (resulting from transpiration and respiration) of potato tubers in individual storage periods (error = mean value +/− 95% of confidence interval).

Table 2. Effect of variety and UV-C irradiation on weight loss (resulting from transpiration and respiration) of potato tubers in individual storage periods.

Variety	Exposition	Time	Loses ($g \cdot g^{-1}$)	Homogeneous Groups					
				1	2	3	4	5	6
Fianna	UV-C	I	0.887	****					
Jelly	UV-C	I	0.927	****					
Fianna	control	I	0.948	****					
Syrena	UV-C	I	0.961	****					
Jelly	control	I	0.977	****					
Syrena	control	I	1.012	****					
Fianna	UV-C	II	1.785		****				
Jelly	UV-C	II	1.849		****				
Fianna	control	II	1.964		****				
Jelly	control	II	1.974		****				
Syrena	UV-C	II	1.991		****				
Syrena	control	II	1.992		****				
Fianna	UV-C	III	2.741			****			
Jelly	UV-C	III	2.804			****			
Fianna	control	III	2.863			****			
Syrena	UV-C	III	2.968			****			
Syrena	control	III	2.998			****			
Jelly	control	III	3.172			****			
Fianna	UV-C	IV	3.649				****		
Jelly	UV-C	IV	3.787				****	****	
Syrena	UV-C	IV	3.971				****	****	****
Fianna	control	IV	4.088				****	****	****
Syrena	control	IV	4.120					****	****
Jelly	control	IV	4.308						****

(****) Arrangement of homogeneous groups (Spjotvoll–Stoline test).

Table 3. Impact of the year of experiment, variety, and UV-C irradiation on weight and number of potato tuber sprouts after storage.

Qualitive Predictor and Interaction	Value of F-Snedecor Test	Probability Test
Free Word	10787.16	0.0000
Year {1}	0.22	0.9276
Variety {2}	12.58	0.0000
UV-C exposition {3}	10.11	0.0001
{1}x{2}	1.43	0.1767
{1}x{3}	1.72	0.1420
{2}x{3}	5.20	0.0004
{1}x{2}x{3}	1.82	0.0680

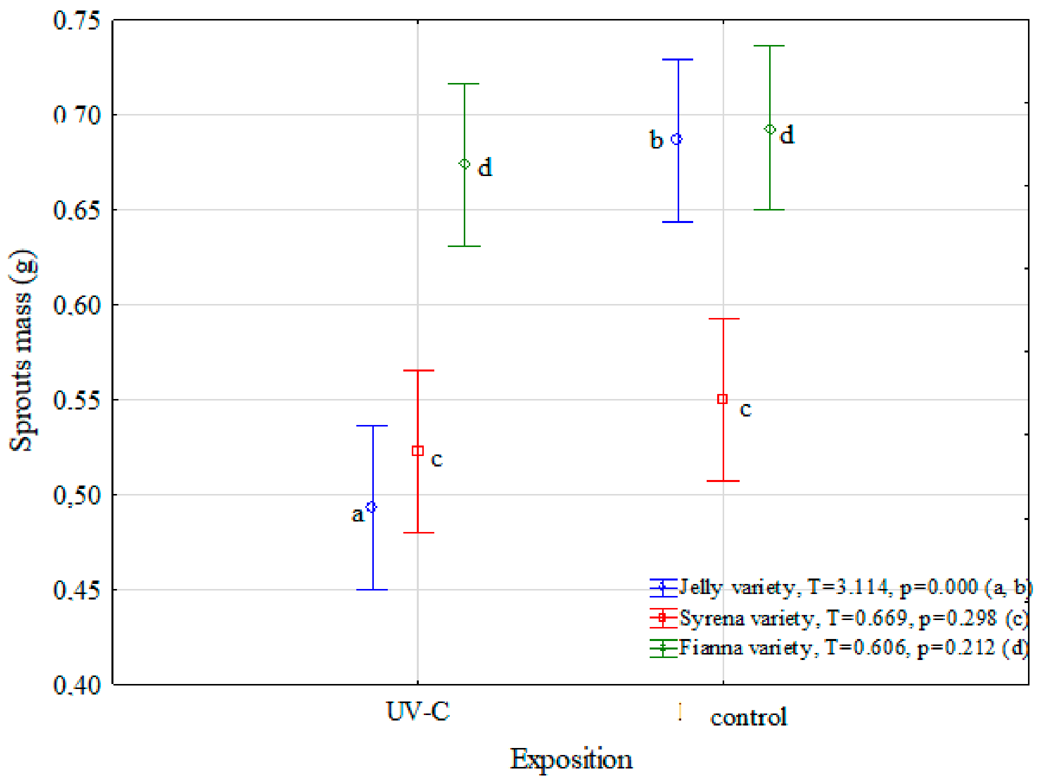


Figure 3. Effect of potato tuber UV-C irradiation on sprout weight after storage (statistically significant difference for the Jelly variety), (error = mean value +/− 95% of confidence interval).

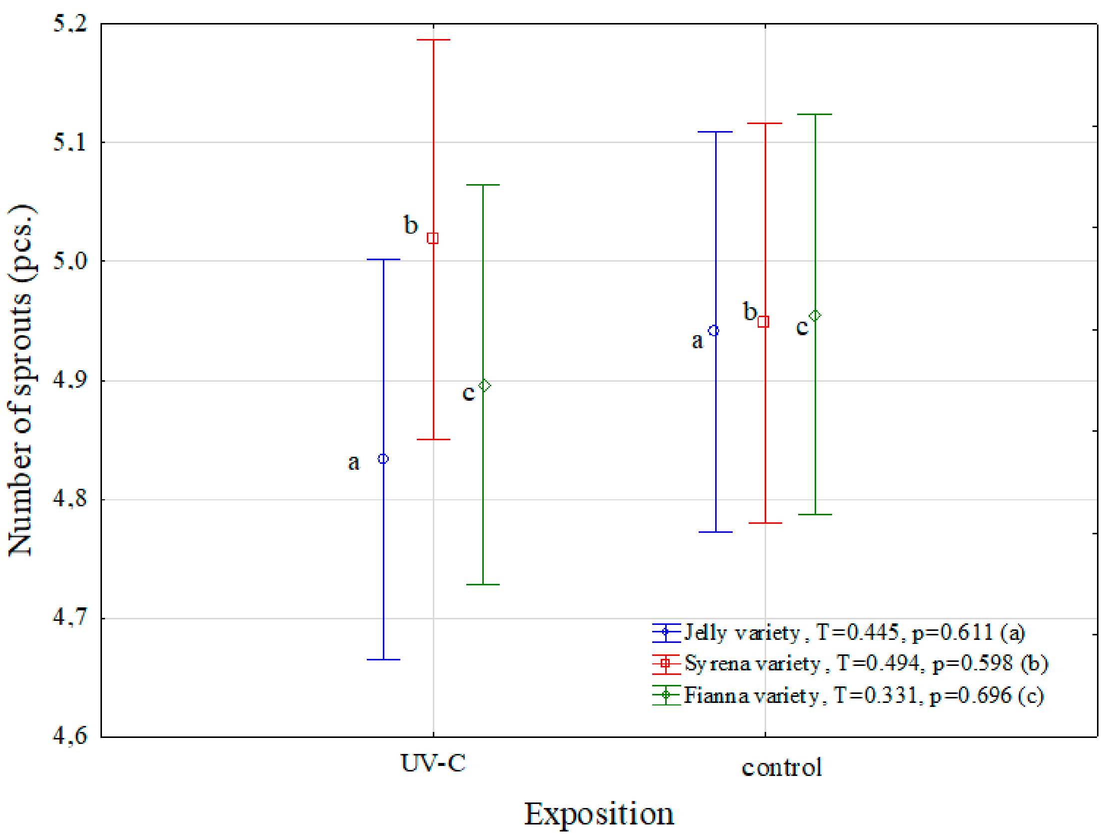


Figure 4. Effect of potato tuber UV-C irradiation on number of sprouts after storage (statistically insignificant differences), (error = mean value +/− 95% of confidence interval).

4. Discussion

The results of the conducted experiment, in which the reduction of natural losses measured after 6.5 months of storage is achieved by means of the UV-C irradiation of potato tubers before storage, were expected to be similar to the results obtained for early and medium-early varieties (Vineta and Ditta) and described by Jakubowski [55]. The tests carried out in this research and the results obtained allowed for a description of the phenomenon causing reduction of natural losses and a determination of the stage of potato storage in which the physical factor, in the form of UV-C radiation, significantly affects the tubers under exposure. The results of the experiment prove that the effects of UV-C on stored potato tubers occur in the final stage (IV) of their storage (Table 2), which corresponds to the phase of tubers awakening and beginning their sprouting. In stage IV of storage, all the tested varieties reacted to UV-C, demonstrating the reduction in natural losses in comparison to the control, and for the Jelly variety, these differences were statistically significant ($F = 2.329$; $p = 0.0301$). The reduction in the weight loss of the pre-treated tubers during storage could occur through changes in the epi- and cuticular wax morphology. Some information on this aspect of treatment are presented in other research, such as Charles et al. [56,57]. Sprouting of the tubers indicates the break of dormancy. Oxidative atmospheres, such as chlorine atmospheres, are known to control sprouting [58].

The analyzed potato tubers reacted to UV-C radiation demonstrating the reduction in sprout weight by 80 $g \cdot g^{-1}$, on average, for all the varieties, which amounts to approximately 14.2% compared to the control. For Jelly tubers, these differences were statistically significant (difference of 194 $g \cdot g^{-1}$, which is approximately 39% compared to the control) (Figure 3). The tubers of Jelly and Fiana varieties subjected to UV-C irradiation were also characterized by a lower number of sprouts compared to the tubers not being under exposure, by 0.11 and 0.05 pcs, respectively. A higher number of sprouts resulting from UV-C irradiation was noted for the tubers of Syrena variety, by 0.07 pcs compared to the control (Figure 4). The results of the experiment suggest that UV-C, in addition to neutralizing pests in areas of damaged potato periderm [55], may act as a sprouting inhibitor, which reduces respiration and, more particularly, transpiration. The obtained results also allow for the conclusion that UV-C does not interfere with the process of tuber transpiration and respiration at earlier stages (I-III) of storage. The inhibitory effect of ultraviolet in the C band may result from the fact that the effect of 253.7 nm wave on a biological object may lead to damaging its DNA chains, and at the same time UV is absorbed by DNA, RNA [59–63], protein, free purine, and pyrimidine bases, acting mutagenetically and inhibiting cell division in the irradiated organism [64–66]. The preliminary tests carried out by Pristijono et al. [41] on freshly harvested potatoes (Solanum tuberosum ′Innovator′) that were exposed to UV-C light revealed that UV-C irradiation significantly affected the number of sprouts. UV-C irradiation also affected the sprout length since irradiated potatoes had significantly shorter sprouts than those of untreated potatoes. Despite the fact that storage conditions were different in this experiment (storage in air 20°C), the authors [41] conclude that these results indicate promise for UV-C as a potential postharvest treatment to reduce the incidence of sprouting in potato tubers.

5. Conclusions

1. A significant impact of potato tuber UV-C irradiation on the size of natural losses was observed.
2. A reduction in potato tuber weight loss caused by transpiration and respiration was shown in comparison to the control sample.
3. Jelly variety reacted to UV-C radiation, demonstrating the reduction in the sprout weight.
4. The result of the experiment indicates that the proposed physical UV-C method can be applied in practice and can be used as a way of reducing the natural defects of stored potato tubers.

6. Patents

Jakubowski T. Patent: The method and device for increasing the storage life of potato tubers with the participation of radiation UV-C (in Polish; Sposób i urządzenie do zwiększania trwałości przechowalniczej bulw ziemniaczanych przy udziale promieniowania UV-C: P.419392, data zgłoszenia 07-11-2016).

Jakubowski T., Sobol Z. Patent: The method for modifying the color of potato products and a device to modify the color of potato products (in Polish; Sposób modyfikowania barwy wyrobów z ziemniaków i urządzenie do modyfikowania barwy wyrobów z ziemniaków: P.425887, data zgłoszenia 11-06-2018).

Author Contributions: Conceptualization, T.J. and J.B.K.; methodology, T.J.; validation and formal analysis, T.J. and J.B.K.; investigation, resources, and data curation, T.J. and J.B.K.; writing—original draft preparation, writing—review and editing, and visualization, J.B.K. All authors have read and agreed to the published version of the manuscript.

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