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The Effect of Light Exposures on the Content of Harmful Substances in Edible Potato Tuber

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Abstract: Background: The impact of light on the content of undesirable substances is particularly important in the case of potatoes available in store where the tubers are exposed to continuous light access. Both washed and unwashed potatoes are available, hence the hypothesis that the amount of harmful substances stored in tubers depends not only on the time of their exposure to light, but also on whether they were washed or not. Methods: In order to verify the hypothesis, laboratory tests were carried out on the tubers of five potato varieties originating from a univariate field experiment. The aim of the study was to analyse the change in the content of total glycoalkaloids (TGA) and nitrates (V) in tubers of five potato varieties depending on the time of light exposition (0, 7, 14 days) and pretreatment of tubers. Results: It has been demonstrated that the content of glycoalkaloids and nitrates in potato tubers depended significantly on the variety, time of exposure to light and pretreatment. Most glycoalkaloids were accumulated in the tubers of the Lord (89.67 mg·kg^{-1}) and Irga (89.05 mg·kg^{-1}) varieties. The time of light exposure significantly influenced the increase in glycoalkaloids and nitrates in the studied potato tubers. The increase in TGA after 14 days ranged from 20.67 mg·kg^{-1} for variety Vinieta to 54.67 mg·kg^{-1} for variety Irga. The increase in nitrates ranged from 11.67 mg·kg^{-1} for variety Bellarosa to 27.50 mg·kg^{-1} for variety Irga. Exposure time affected the content of glycoalkaloids in a parabolic manner and the content of nitrates in a linear manner.

Keywords: glycoalkaloids; nitrates (V); *Solanum tuberosum* L.; variety; unwashed and washed tubers

1. Introduction

Potatoes are the basis of many diets around the world due to the content of nutrients, such as carbohydrates, protein, dietary fibre, vitamins and minerals [1–3]. In addition to the nutrients in potato tubers, there are also natural undesirable substances: nitrates (V) and glycoalkaloids [4–6]. Nitrates (V) are not directly toxic to humans, but under the influence of the intestinal microflora they may be reduced to nitrates (III), with the participation of which the carcinogenic nitrosamine may be formed [7,8]. The safe level of nitrates (V) in potatoes directed for consumption should not exceed 200 mg NO_3^- kg^{-1}. The content of these substances can significantly increase above the recommended

level, among others, under the influence of the climatic, agrotechnical intensity of nitrogen fertilization or improper storage of tubers [7,9–11].

Glycoalkaloids are also an anti-nutritional substance. They are a mixture of many solanidine derivates, and due to their similar structure and physicochemical properties, they are often referred to as total glycoalkaloids (TGA) [12]. Glycoalkaloids (TGA), are toxic steroidal glycosides naturally occurring in the entire *Solanacea* family [13–17]. Glycoalkaloids, found in leaves, stems, flowers, tubers and sprouts, play a role in plant resistance to bacterial and fungal diseases and pests; however, in excessive amounts, they worsen taste, and a concentration above 200 $mg \cdot kg^{-1}$ of fresh weight has toxic effects on the human body [18–20]. Regulation of the content of glycoalkaloids is possible, as these compounds are synthesized under the influence of external factors, i.e., agrotechnics, storage, mechanical damage and the effects of light exposure during vegetation and storage [21,22].

Chlorophyll and glycoalkaloid synthesis in potato *(Solanum tuberosum* L.) tubers occur in direct response to light. The two processes are concurrent, but independent [23]. The greening of tubers under the influence of light is the result of the accumulation of chlorophyll in the skin and tuber pulp [24,25]. It has been proven that, under the influence of sunlight, potato tubers turn green and the accumulation of glycoalkaloids increases significantly compared to the control [23,25].

The effect of light on the content of undesirable substances is particularly important in the case of potatoes available in stores where tubers are exposed to continuous access of light [26]. Washed and unwashed tubers are available in trade, which may accumulate harmful substances to varying degrees under the influence of exposure to light. Therefore, a study was undertaken to analyse the change in the content of glycoalkaloids and nitrates (V) in tubers of five potato varieties depending on the time of light exposure and the pre-treatment method. The research was aimed at checking whether the long-term exposure of potato tubers to light will increase the content of anti-nutrition substances in tubers to a critical level in both washed and unwashed potato tubers.

2. Materials and Methods

The tests were carries out in laboratory conditions. The material for testing included tubers of edible potato varieties originating from a one-way field experiment, which was conducted in accordance with the recommendations of integrated edible potato cultivation and European Union standards. The following factors were examined in the conducted experiment:

Factor A—potato varieties:

A_1—Bellarosa: a variety characterized by large round oval shaped tubers and shallow eyes. Ware potatoes are characterized by pink scabrous skin and yellow flesh. Starch content 12.1%,

A_2 —Irga: a variety characterized by mid–large, round oval shaped tubers with shallow eyes, pink skin and creamy flesh. Starch content 13.8%,

A_3—Irys: a variety characterized by large, oval tubers with good regular shape, yellow skin and light-yellow flesh. Starch content 12.9%,

A_4—Lord: a variety characterized by very large, oval round tubers with good regular shape, fairly shallow eyes, yellow skin and light-yellow flesh. Starch content 11.8%.

A_5—Vinieta: a very tasty variety characterized by large oval shaped tubers and yellow flesh. Ware potatoes are characterized by slightly scabrous yellow skin. Starch content 12.7%.

Factor B—time of light exposure (B_1—0 days, B_2—7 days, B_3—14 days).

Factor C—pre-treatment method (C_1—unwashed tubers, C_2 – washed tubers).

Forty tubers of each potato variety were tested, 20 tubers were washed and dried, and 20 were left unwashed, then one batch of tubers (control) was subjected to chemical analysis for the content of nitrates and glycoalkaloids, while the remaining two batches of tubers were subjected to a weekly and two-week exposure to light under fluorescent lamps, imitating lighting in supermarkets, with an intensity of 15 W (density of photon flux of 13 $\mu mol.m^{2 \cdot} s^{-1}$). Tubers were placed on trays and irradiated for ten hours a day. The content of nitrates and glycoalkaloids was determined at the time of setting up the experiment and after 7 and 14 days of exposure.

Chemical analyses were performed using fresh material in three replications at the Chemical Laboratory of the Department of Agrotechnology. The nitrates (V) content in tubers was determined in fresh matter with an ion-selective nitrate electrode and a silver-silver chloride reference electrode [27]. The content of glycoalkaloids in tubers was determined by the Bergers method [28].

Each tuber has been grated on a plastic grater. A total of 10 g of the mass has been taken and flooded with methanol and left for 10 minutes. After 10 minutes, it has been filtered. Methanol has been added to a total volume of 50 cm^3. Then, 5 cm^3 of the extract has been evaporated at 50 °C. The determinations have been made on a spectrophotometer, the wavelength of which has been set to 620 nm. Ten grams of grated tuber weight has also been taken for the determination of nitrates. Nitrates have been determined using a single-selective nitrate electrode and a silver chlorine reference electrode with sodium salicylate in concentrated H_2SO_4.

The statistical analysis of the results was based on a three-factor analysis of variance for a completely random system using the STATISTICA 12, 5 program in accordance with the following mathematical model:

$$y_{ijlp} = m + a_i + b_i + c_l + ab_{il} + ac_{il} + bc_{il} + abc_{ijl} + e_{ijlp} \quad (1)$$

where:

y_{ijl}—the value of the examined characteristic (content of glycoalkaloids, nitrates);
m—population average;
a_i—the effect of the i-th level of factor A (variety);
b_j—the effect of the j-th level of factor B (exposure time);
c_l—the effect of the l-th level of factor C (pre-treatment);
ab_{ij}—the effect of the interaction of factor A and B;
ac_{il}—the effect of the interaction of factor A and C;
bc_{jl}—the effect of the interaction of factor B and C;
abc_{ijl}—the effect of the interaction of factor A, B and C;
e_{ijlp}—the random error [29,30].

The exposure time was a quantitative factor and changed by a constant amount. Hence, in the case of its significance, it was possible to determine regression equations with respect to the quantitative factor, which described the relationship between the content of glycoalkaloids and nitrates in varieties depending on the exposure time. In this type of analysis, the system of orthogonal polynomials is used.

Because the quantitative factor was present on 3 levels, its impact could have been (according to the assumptions of the analysis) linear or parabolic. Therefore, the first ($\xi_{1)}$ and second degree (ξ_2) polynomials were determined in the form of:

$$\xi_2(x) = k(x)\lambda_1 \quad (2)$$

where:

$$k(x) = k(x) = \frac{1}{h}(x_i - \bar{x}), \quad (3)$$

$$\xi_2(x) = \left[k^2(x) - \frac{n^2 - 1}{12}\right]\lambda_2 \quad (4)$$

where:

n—the number of values;
x_i, h—the spread of the quantitative factor.

The coefficients λ_1 and λ_2 were selected so that the polynomials ξ_j only took on integer values. To determine the nature of the factor's effect, the multiple regression equations were determined in relation to the polynomials $\xi_j(x)$ according to the formula [31]:

$$m(x) = a_0 + a_1\xi_1(x) + a_2\xi_2(x) \quad (5)$$

3. Results

Statistical analysis showed that the content of glycoalkaloids in potato tubers depended significantly on the variety, the time of exposure to light and pre-treatment. The cooperation of the variety and duration of light operation, as well as the variety, time of light operation and pre-treatment of potato tubers proved to be important (Table 1).

Table 1. Content of glycoalkaloids depending on the variety, pre-treatment and the time of exposure to light (mg·kg^{-1} in fresch matter.

Pretreatment Method	Average for Content of Glycoalkaloids (mg·kg^{-1})					
	Variety					Average
	Bellarosa	Irga	Irys	Lord	Vinieta	
	Time of light exposure 0 days					
Unwashed	27.00	55.00	45.00	59.00	22.00	41.60 ± 15.31
Washed	27.00	55.00	45.00	59.00	22.00	41.60 ± 15.31
Average	27.00 ± 0.87	55.00 ± 0.92	45.00 ± 0.88	59.0 ± 0.78	22.00 ± 0.68	41.60 ± 15.31
	Time of light exposure - 7 days					
Unwashed	47.90	95.02	85.04	98.03	38.02	72.80 ± 25.81
Washed	58.00	110.01	90.03	105.03	42.03	81.02 ± 27.61
Average	53.02 ± 5.54	102.52 ± 8.34	87.54 ± 2.88	101.50 ± 3.70	40.03 ± 2.36	76.91 ± 26.52
	Time of light exposure - 14 days					
Unwashed	49.02	99.31	88.02	108.00	40.03	76.93 ± 28.20
Washed	61.03	120.01	94.04	109.01	45.04	85.83 ± 29.40
Average	55.03 ± 6.63	109.66 ± 11.38	91.03 ± 3.40	108.51 ± 1.04	42.67 ± 2.80	81.38 ± 28.70
	Time of light exposure (0–14 days)					
Average for unwashed tubers	41.33	83.11	72.67	88.33	33.44	63.78 ± 28.17
Average for washed tubers	48.67	95.00	76.33	91.00	36.33	69.47 ± 31.50
Average for variety	45.00 ± 13.94	89.05 ± 26.10	74.50 ± 21.65	89.67 ± 22.62	34.89 ± 9.62	66.62 ± 5.54

$LSD_{0.05}$ for: varieties = 1.20; time of light exposure = 0.77; pre-treatment method = 0.55; variety x time of light exposure = 1.70; variety x pre-treatment method = n.s.; time of light exposure x pre-treatment method = n.s.; variety x time of light exposure x pre-treatment method = 1.71.

Most glycoalkaloids were accumulated in the tubers of the Lord and Irga varieties (89.67 mg·kg^{-1} of fresh weight) and the least Vinieta variety (34.89 mg·kg^{-1} of fresh weight). The Lord and Irga varieties did not differ significantly in this respect. The content of glycoalkaloids, irrespective of the variety, increased significantly with the extension of the exposure time (on average 39.77 mg·kg^{-1}) and the method of pre-treatment (on average 5.69 mg·kg^{-1}). On average, more glycoalkaloids were recorded in washed (69.47 mg·kg^{-1}) than unwashed (63.78 mg·kg^{-1}) tubers. The significance of the interactions of the variety and exposure time indicates that differences in the content of glycoalkaloids between varieties were differentiated by the exposure to light. On the first day of the experiment, the varieties differed significantly between themselves with the content of glycoalkaloids. On average, the biggest amount of this compound was observed in the Lord variety, and the smallest in the Vinieta variety. Both after 7 and 14 days of exposure, the biggest and comparable content of glycoalkaloids was observed in the Irga and Lord varieties. Significantly less glycoalkaloids after that time were found in tubers of the Vinieta and Irys varieties.

Significance of interactions of varieties, time and treatment proves that the varieties differed in the tendency to accumulate glycoalkaloids over time depending on whether they were washed or not. All varieties in each of the times accumulated more glycoalkaloids when they were washed. The only exception was the Lord variety in which the content of glycoalkaloids in the third time period (after 14 days) was the same regardless of whether the tubers were washed or not. The exposure time influenced the content of glycoalkaloids in tubers of the tested varieties in a parabolic manner.

The optimal theoretical values of the number of days in which the tubers accumulated their greatest amount, determined on the basis of the functions, ranged from 10.70 days for the Bellarosa variety to 12.30 days for the Lord variety for unwashed tubers. In the case of washed potatoes, these values ranged from 11.09 days for the Lord variety to 11.79 for the Irga variety. In conclusion, it can be stated that, regardless of whether the tubers were washed or not, in all varieties, the maximum accumulation of glycoalkaloids occurred after 11 days of exposure (Figures 1 and 2, Table 2).

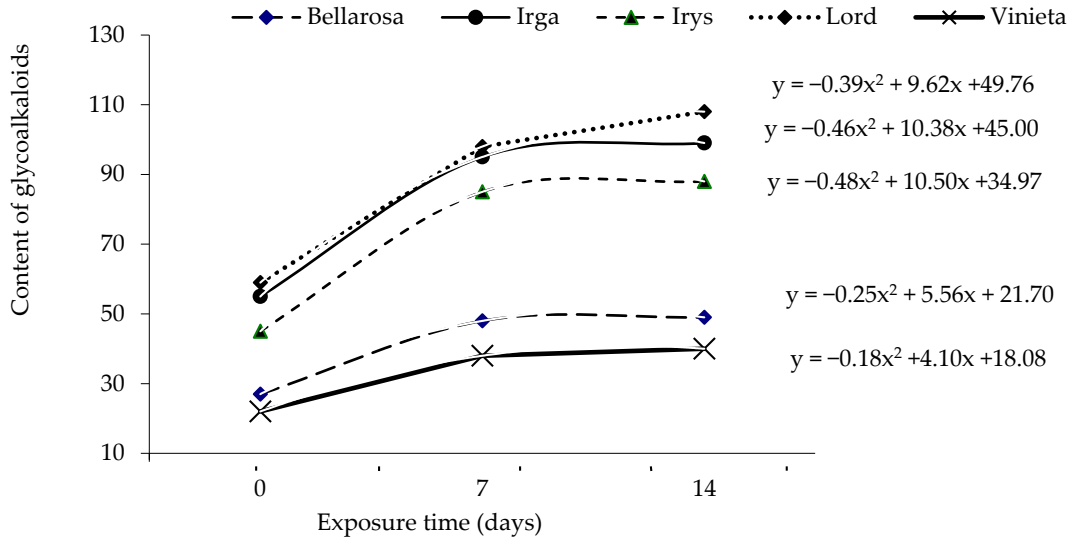

Figure 1. Equations of the relationships between the time of exposure to light and the content of glycoalkaloids in unwashed tubers of the tested varieties (mg·kg^{-1} FM).

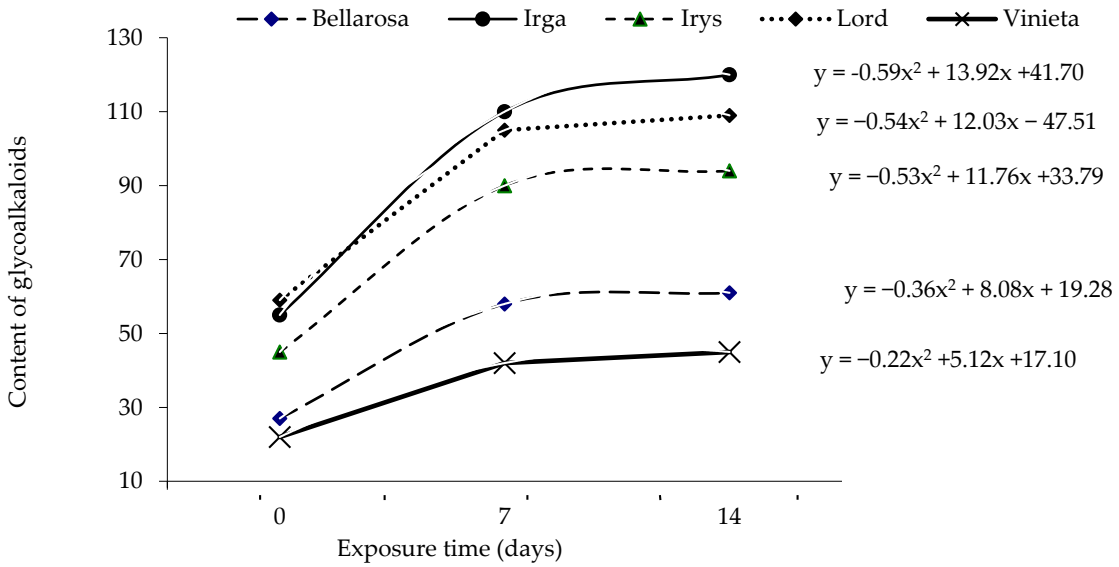

Figure 2. Equations of the relationships between the time of exposure to light and the content of glycoalkaloids in washed tubers of the tested varieties (mg·kg^{-1} FM).

Table 2. Content of nitrates depending on the variety, pre-treatment method and time of exposure to light (mg·kg^{-1} in fresch matter).

Pre-Treatment Method	Average for Content of Nitrates (mg·kg^{-1})					
	Variety					
	Bellarosa	Irga	Irys	Lord	Vinieta	Average
	Time of light exposure - 0 days					
Unwashed	55.00	105.00	70.00	95.00	110.00	87.00 ± 21.87
Washed	55.00	105.00	70.00	95.00	110.00	87.00 ± 21.87
Average	55.00 ± 0.88	105.00 ± 0.97	70.00 ± 1.01	95.00 ± 0.97	110.00 ± 0.96	87.00 ± 21.87
	Time of light exposure - 7 days					
Unwashed	65.01	115.02	85.01	107.03	124.02	99.22 ± 22.20
Washed	62.02	110.03	90.03	105.04	130.01	99.43 ± 23.50
Average	63.52 ± 1.87	112.53 ± 2.88	87.52 ± 2.89	106.04 ± 1.41	127.02 ± 3.40	99.32 ± 22.44
	Time of light exposure - 14 days					
Unwashed	68.33	124.02	98.01	110.02	139.01	107.88 ± 42.92
Washed	65.00	120.01	94.01	109.00	136.02	104.81 ± 25.04
Average	66.67 ± 1.34	122.00 ± 0.94	96.00 ± 1.24	109.50 ± 1.37	137.50 ± 1.68	106.34 ± 24.60
	Time of light exposure (0–14 days)					
Average for unwashed tubers	62.78	114.67	84.33	104.00	124.33	98.20 ± 22.10
Average for washed tubers	60.67	111.67	84.67	103.00	125.33	97.07 ± 20.23
Average for variety	61.72 ± 5.32	113.17 ± 7.45	84.50 ± 1.33	103.50 ± 6.44	124.83 ± 11.85	97.54 ± 24.00

$LSD_{0.05}$ for: varieties = 1.17; time of exposure to light = 0.75; pre-treatment method = 0.49; variety x time of light exposure = n.s.; variety x pre-treatment method = 1.35; time of light exposure x pre-treatment method = 0.89; variety x time of light exposure x pre-treatment method = 1.66.

All varieties differed significantly between the contents of nitrates. The largest amount of this ingredient was collected by the Vinieta variety (an average of 124.83 mg·kg^{-1} of fresh weight) and the least was collected by the Bellarosa variety (an average of 61.72 mg·kg^{-1} of fresh weight).

Similar to the content of glycoalkaloids, the nitrates content increased significantly with the prolongation of the exposure time to light. The significance of the interaction of varieties and the pre-treatment indicates that there is a difference in the accumulation of this component in the tubers of varieties depending on whether they have been subjected to washing or not. In the Irys, Lord and Vinieta varieties, there were no differences in the accumulation of nitrates by the washed and unwashed tubers. The Bellarosa and Irga varieties accumulated more nitrates in unwashed tubers: 62.78 and 111.67 mg·kg^{-1} of fresh weight, respectively.

The content of nitrates in washed and unwashed tubers after 7 days, regardless of the variety, was comparable. After 14 days, on average, more nitrates were accumulated by tubers of unwashed tubers compared to washed ones. Differences in the accumulation of nitrates between washed and unwashed tubers were found only in the Lord variety after 14 days of exposure (Figures 3 and 4).

The effect of the light exposure on the content of nitrates in tubers of unwashed varieties for all varieties was linear. In the Vinieta, Irga and Irys varieties, increasing the exposure time by 1 day caused an average increase in nitrates by about 2.00 mg·kg^{-1} of fresh weight. In the Bellarosa and Lord varieties, increasing the exposure time by one day caused an increase in the concentration of nitrates by about 1.00 mg·kg^{-1} of fresh weight.

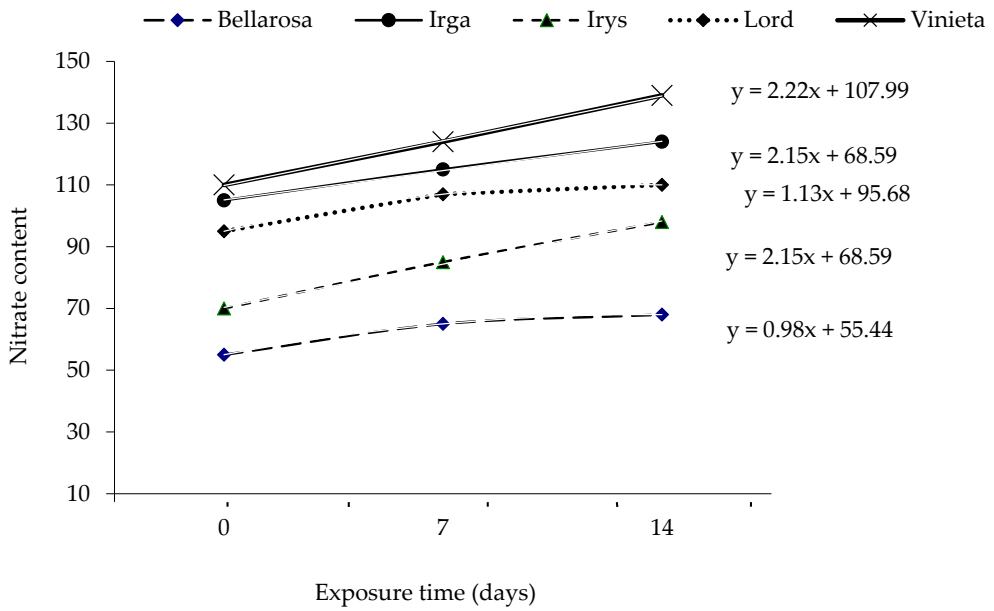

Figure 3. Equations of the relationship between the time of exposure to light and the content of nitrates in unwashed tubers of the studied varieties (mg·kg^{-1} FM).

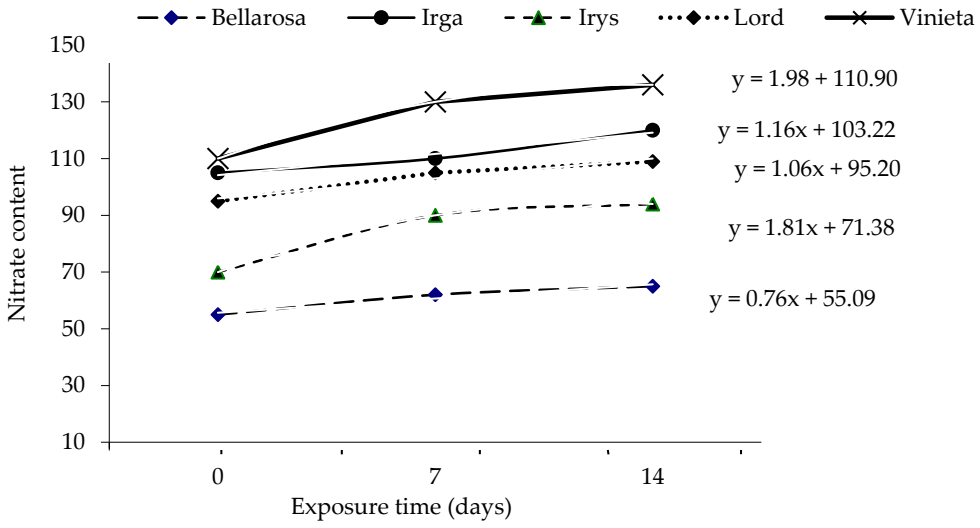

Figure 4. Equation of the relationship between the time of exposure to light and the content of nitrates in washed tubers of studied varieties (mg·kg^{-1} FM).

4. Discussion

Light is one of the factors that may contribute to increasing total glycoalkaloid (TGA) levels in potato tubers. According to Precival [32], exposure of tubers to artificial light can cause up to a 300-fold increase in these substances in tubers. The conducted analyses allowed us to examine whether potatoes exposed to artificial light after a sufficiently long time (14 days) contain a safe amount of anti-nutritional substances. The TGA content in the tubers of the analysed cultivars did not exceed the critical value and varied depending on the cultivar from about 35.00 to about 90.00 mg·kg^{-1} of fresh weight. Among the varieties tested, the most TGA was accumulated by the Lord and Irga varieties, and significantly less by the Irys, Bellarosa, and Vinieta varieties. Many studies also confirm differences in glycoalkaloid content between varieties. Kirui et al. [33] observed that, among the varieties of potato grown in Kenya, the amounts of TGA ranged from 53.00 to 153.00 mg·kg^{-1} of fresh weight.

The obtained results are fully supported by the research of Zgórska et al. [15], Skrabule [34], Wierzbicka [35], and Hamouz et al. [36], who confirmed the decisive role of the genotype in the content of glycoalkaloids in potato tubers. The influence of the genotype can be explained by the strong heredity of this trait, which, according to Sanforf et al. [37] can reach up to 89%.

It has been proven that with the longer exposure time of tubers, the TGA content in tubers of all varieties increased, but, even after 14 days of exposure, the limit value was not exceeded. Our research also confirms that the way tubers were prepared for storage affected the TGA content. Regardless of the variety, more glycoalkaloids were found in washed tubers than the unwashed ones. This phenomenon can be explained by the fact that the skin of the tubers is somewhat protected by impurities and is less exposed to direct light and mechanical damage. These results were confirmed by the studies of Zgórska et al. [26], who found that the exposure of tubers to light and mechanical damage caused a significant increase in the content of glycoalkaloids in tubers of all tested varieties. In practice, this means that mechanical damage and light, to which tubers are exposed during harvesting, transport, sorting and exposure in shops, double the level of glycoalkaloids found in tubers immediately after harvesting. Moreover, the studies by Rytel [38] confirmed that the pre-treatment method affects the level of TGA in potato tubers.

The research provided information on the content of glycoalkaloids in tubers of potato varieties depending on the time of their exposure to light and the method of pre-treatment (washed and unwashed), i.e., the most important factors that are the subject of commercial potatoes. The analysis of orthogonal polynomials shows that, in all varieties, both washed and unwashed, the TGA content has been parabolic since exposure. This indicates that there is a moment when the accumulation of these compounds research its maximum. Based on the conducted research, it was found that the maximum accumulation of TGA occurs after about 11 days of exposure to light. These results are a valuable source of information for consumers. These studies show that even a few days of exposure to light at the point of sale does not cause a significant increase in the TGA content in potato tubers. The conducted tests contribute to further analyses covering the reaction of other varieties to different periods of light exposure and changes in the chemical composition of tubers. According to Haddadin et al. [39], the content of TGA in potato tuber skin under the influence of light can increase up to ten times compared to tubers stored in the dark. The high content of glycoalkaloids eliminates tubers for consumption, but they can be a valuable source of natural substances used as an antibacterial agent against *Staphylococcus aureus* bacteria, which is confirmed by the latest research by Ismail et al. [40].

The conducted research on the change in the content of nitrates in potato tubers under the influence of light is a novelty, as there are no reports in the literature regarding the exposure of light to the content of nitrates.

The fact that as the exposure time increased, the nitrate content in tubers increased, which is noteworthy, is evidenced by the linear nature of the exposure time effect. Such a reaction was observed in all varieties, both in washed and unwashed tubers. The impact of the varietal factor on the value of the discussed feature was noted by Gugała and Zarzecka [9], Järvan and Edesi [41], Sawicka and Mikos-Bielak [42], and Simson et al. [43]. In unwashed potatoes, an increase in irradiation time by one day resulted in an increase in nitrate concentration depending on the variety from 2 to 1 mg·kg^{-1} of fresh weight; in washed potatoes, this increase was smaller. It can be assumed that there are reactions between light and impurities (soil or dirt) found on the tubers that lead to the growth of nitrates in the tubers. This assumption can be confirmed by the obtained results, which confirm that more nitrates were found in unwashed tubers (on average, 98.20 mg·kg^{-1} of fresh weight) than the washed ones (97.07 mg·kg^{-1} of fresh weight). The treatment of tubers (washing) resulted in a reduction in the nitrate amount. This relationship can also be seen in the Rytel [38] and Jarych-Szyszka [44] studies, in which the treatment of tubers (peeling and cooking) caused an increase in the content of nitrates (V) by about 20% and 30%.

5. Conclusions

The content of glycoalkaloids and nitrates (V) in potato tubers depended significantly on the variety tested in the experiment. The time of light exposure significantly impacted the increase in the content of glycoalkaloids and nitrates in the studied tubers of edible potato. The exposure time significantly affected the content of glycoalkaloids in a parabolic manner, and the content of nitrates was of a linear nature. The content of harmful substances was also significantly impacted by the pre-treatment methods. A larger amount of glycoalkaloids was accumulated by the washed tubers, while, for nitrates, a larger amount was accumulated by the unwashed tubers.

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