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Effect of Drip Fertigation with Nitrogen Application on Bioactive Compounds and the Nutritional Value of Potato Tubers before and after Their Long-Term Storage

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Abstract: The nutritional value and the content of bioactive compounds in potato tubers are influenced by many soil, climate and agrotechnical factors. This study investigated the effect of drip irrigation and nitrogen fertilization by broadcasting and fertigation on the content of dry matter, starch, monosaccharides, total sugars, vitamin C, polyphenolic compounds, chlorogenic acid and antioxidant activity in tubers of "Augusta" potatoes. Additionally, the magnitude of the changes in the tested components during their long-term storage (6 months) was also assessed. Drip irrigation had a significant positive effect on the content of dry matter, starch, vitamin C, monosaccharides, sucrose, total sugars, total polyphenols, chlorogenic acid and antioxidant capacity. Compared to broadcasting fertilization, fertigation significantly increased the content of vitamin C, total polyphenols and chlorogenic acid, as well as the antioxidant activity of potato tubers. Long-term storage contributed to a decrease in the tested components. The exception was the content of monosaccharides, where a more than twofold increase was noted, especially in the case of irrigated tubers. The results of the research showed a beneficial effect of drip irrigation and fertigation on the content of bioactive compounds and the nutritional value of "Augusta" potato tubers.

Keywords: chlorogenic acid; dry matter; FRAP; polyphenolic compounds; *Solanum tuberosum* L.; sugars; vitamin C

1. Introduction

The potato (*Solanum tuberosum* L.) is a species characterized by quite high water needs over a wide period of growth and development. The period from the closure of the rows to the beginning of flowering of plants generally corresponds to the period of tuber setting (tuberization) and is the beginning of the period of high water needs of potato plants and their high sensitivity to drought. Drought around the tuberization stage, during the 3–4 weeks beginning about 1 week before tuberization starts, may result in the formation of a smaller number of tubers and an increase in tuber infection with common scab. If at that time there is a deficit of rainfall, which causes the soil moisture to drop below 60%

of the field water capacity, then the potato crop should be irrigated [1]. The period from the beginning of flowering to the yellowing of the plants is the period in which the potato plants accumulate their yield; i.e., the tubers increase in size and weight. During this period, the soil moisture should be at the level of about 70% of the field water capacity [1]. The water needs of potato are the greatest at that time, and the plants are most sensitive to drought (the daily requirement of plants exceeds 3 mm of precipitation). If a drought period occurs during this time or the distribution of rainfall is uneven, it has a negative impact on the size, yield and quality of tubers [1].

The method of supplementing the amount of rainfall and equalizing its distribution depending on the needs of potato plants, and thus obtaining a high and stable yield with favorable tuber quality characteristics, is plantation irrigation with the use of various types of irrigation devices [2]. Currently, in potato plantations, sprinkler irrigation is most often used, which unfortunately causes large water consumption and losses through evaporation and may have negative side effects in the form of leaf burn or leaf disease development [3]. In addition, the potato root system is relatively shallow, with approximately 85% of the roots clustered in the top 30 cm of soil [4,5], which are more likely to leak nutrients and exhibit leaching than deep-rooted species arable crops [6]. Therefore, proper water and fertilizer management for potato production is very important, especially on sandy soils. Drip irrigation is considered the most precise technique for plant irrigation. This method of irrigation ensures that the water reaches the plant roots and is quickly drawn up and that there is no loss due to evaporation from the plant surface, so it is a water-saving system. Moreover, this method of water application does not flatten the ridges and the tubers do not turn green. During drip irrigation, the above-ground part of the plants is not sprayed, and thus the risk of plant infection with potato blight is much lower. By reducing the risk of plant infestation with potato blight, the amount of fungicide spray can be reduced [7]. The drip system can also be used for fertigation; i.e., mineral fertilizers (especially nitrogen) can be applied with the water. It was found that fertigation is several times more effective in terms of potato tuber yield than traditional fertilization applied in a solid form [8–10]. Research shows that the drip irrigation system is economically profitable in potato production [7], as potatoes are more likely to leach nutrients than deep-rooted species of arable crops. Water-soluble fertilizers in the concentrations required by the plants are delivered with each irrigation or at regular intervals by drip irrigation to the root zone, in accordance with the physiological requirements of the crops. This makes it easier to match fertilizer application with plant nutrient needs, reduces nutrient loss and can result in relatively high fertilizer application and efficiency; furthermore, it does not flatten the ridges [11,12]. Properly managed drip fertigation can reduce soil water fluctuations and avoid excessive water application, thereby retaining fertilizer in the root zone for longer, reducing overall fertilization rates and minimizing negative environmental impacts [13–22].

Due to the savings in water and fertilizers, it should be expected that fertigation may be one of the basic components of the precise technology of cultivating many plant species, including potato. Undoubtedly, an obstacle to the widespread use of fertigation is the high investment expenditure, resulting mainly from the purchase of drip lines and their installation; therefore, further improvements and modifications to this system should be pursued [23–26].

During the long-term storage of potato tubers, natural changes occur due to the respiration and transpiration process. These are accompanied by weight loss and biochemical changes, the sizes of which depends on many factors. With extended storage periods, weight losses may increase due to the germination of potato tubers.

Taking into account the above issues, studies were carried out to analyze the effect of nitrogen fertilization by broadcasting and in liquid form (fertigation), both under drip irrigation and the natural system of soil moisture conditions (control—without irrigation), on the content of nutrients and bioactive compounds in tubers of the potato cultivar

Augusta. The level of changes in the content of tested chemical compounds during the long-term storage of potato tubers was also determined.

2. Materials and Methods

2.1. Experimental Site and Design

The field experiment was conducted in 2011–2013 in Kruszyn Krajeński (53°04′53″ N, 17°51′52″ E), located near Bydgoszcz in the central part of Poland. This region has a precipitation deficit and very unfavorable water balances [12–18]. The potato (*Solanum tuberosum* L.)—the mid-early cultivar Augusta—was grown on a Cambic Phaeozem soil made of alluvial sand. The water retention capacity of the soil was very low, as the content of water available for plants was 54 mm per 1 m, including readily available water of only 32 mm. The cultivation was carried out in accordance with the standard crop management practices suggested for potato under Polish guidelines.

The field experiment was designed using a split-plot system with four replications. In the study, two factors were applied, each in two variants. The first factor was the drip irrigation used, with two treatments: (1) without irrigation (control) and (2) with drip irrigation. The second factor was the method of nitrogen fertilization used, with two treatments: (1) nitrogen fertilization by broadcasting and (2) nitrogen fertilization by drip fertigation.

The single plot area intended for harvest was 1.5 m × 7.5 m. Potato plants grew in rows between which the distance was 75 cm; the distance between the plants in the rows was 30 cm. For all the experimental treatments, the nitrogen fertilization dosage was 120 kg N ha^{-1}. The nitrogen fertilizer (ammonium nitrate: N-NH_4—17.2% and N-NO_3—17.2%) was supplied at three single intervals, each of 40 kg N ha^{-1}. The first rate of fertilizer was applied prior to emergence by broadcasting in all the plots. The second rate of fertilizer was applied at the end of June and the third rate in mid-July by broadcasting or by drip fertigation. Fertigation was performed using a drip irrigation network and proportional mixing feeders. The phosphorus–potassium fertilization that was carried out by broadcasting in the spring before plant cultivation was 100 kg P ha^{-1} (superphosphate), and 150 kg K ha^{-1} (potassium salt) and was the same for all treatments. In autumn 2010, farmyard manure (30 t ha^{-1}: 0.5% N; 0.1% P_2O_5; 0.0437% P) was mixed with soil in the field where the experiment was carried out. When using manure in a dose of 30 t ha^{-1}, the 150 kg of N and 33 kg of P were added.

A "T-Tape" linear drip was applied for drip irrigation treatment. The distance between the emitters was 20 cm and the flow rate was 5 L m^{-1} h^{-1} (at a pressure of 1 bar). A single tensiometer (Soil Moisture Equipment Corp, Santa Barbara, CA, USA) was installed on each plot, which determined the start of the single irrigation treatments. Tensiometers used in the experiment did not allow the soil matric potential to drop below −30 kPa [19]. The filters of the tensiometers were placed in the soil at a depth of 25 cm. The applied drip irrigation moistened the soil layer to a depth of 30 cm, and the soil wetting was about 50% of the space among the rows. The average seasonal drip irrigation norm (sum of single rates) during the three years of the study was 61.1 mm and, depending on the structure of precipitation, ranged from 50.0 mm in 2011 to 76.5 mm in 2013 and from 50.0 mm in 2011 to 76.5 mm in 2013.

2.2. Weather Conditions

The information on the air temperature and precipitation in the years of the study was presented by Rolbiecki, et al. [15].

2.3. Storage Conditions

Potato tubers were harvested at full physiological maturity, and samples (10 kg) were taken for storage from each plot. The tubers were then stored in air conditioning chambers located in the Department of Microbiology and Food Technology, Faculty of Agriculture and Biotechnology of the Bydgoszcz University of Sciences and Technology. A

constant temperature and relative air humidity were then maintained over 6 months of storage, according to the requirements of potato tubers, which were stored at +6 °C with 95% relative air humidity (Rh).

2.4. Sample Preparation

The tubers were cut into 1 cm-thick slices and freeze-dried (Christ Alpha 1-4 LSC, Donserv, Warsaw, Poland) in order to achieve a constant dry weight. Freeze-dried samples were then ground into flour using an electric grinder (Chemland, Type FW 177, Stargard, Poland) and then used for chemical analysis. The obtained flour samples were then all stored in sealed plastic bags in desiccators before analysis. All assays were carried out in three laboratory replications.

2.5. Determination of Dry Matter

Dry matter content was determined according to EAPR [27]. Five tubers per plot were washed, dried and cut into cubes. The cubes were homogenized in a laboratory mixer until homogenous pulp was obtained. About 10 grams of the pulp was poured into a Petri dish and then heated at 60 °C for 15 h; then, the oven temperature was raised to 105 °C for 3 h, and then the Petri dish with dry potato was cooled down to room temperature in desiccators and weighed. The total dry matter was calculated according to the EAPR [20].

2.6. Determination of Starch

Starch determination was conducted according to ICC-Standard no. 123 (1994) [28]. Freeze-dried potato flour (2.5 g) was weighed in a 100 mL volumetric flask. Fifty milliliters of 1.124% HCl (Merck, Darmstadt, Germany) was added to the flask. The starch was hydrolyzed by cooking in boiling water for 15 min. During the first 8 min, the flask was shaken horizontally. After cooling to room temperature, the suspension was cleared by adding 2 mL of 10% wolframato-phosphoric acid (Carl-Roth, Karlsruhe, Germany). Distilled water was added to the 100 mL mark, and the suspension was then filtered with filter paper no. 595 $\frac{1}{2}$ (Schleicher & Schuell, GmbH, Dassel, Germany). The optical rotation of the solution containing monosaccharide was measured with the Polarimeter P1000 Krüss Optronic (Merazet, Poznan, Poland). The starch content was calculated using the following formulas (1) and (2):

$$C = \frac{\alpha}{[\alpha]20D} \times l, \quad (1)$$

where:

C = concentration (g mL^{-1});
α = optical rotation of the solution;
$[\alpha]20D$ = specific rotation of hydrolyzed potato flour at 20 °C, which equals 181.8°;
l = the polarimeter tube length (dm).

$$\text{Starch content} = C \times \text{Vext.} \times \frac{1000}{W}, \quad (2)$$

where:

C = concentration (g mL^{-1});
Vext. = extraction volume (mL);
W = weight of sample (kg).

2.7. Determination of Ascorbic Acid

L-ascorbic acid was determined by titration with 2,6-dichlorophenolindophenol solution (DIP). Five tubers were peeled and minced. Five grams of the mince was sampled and immersed in 20 mL 2% oxalic acid (Merck, Darmstadt, Germany). The mixture was homogenized in ultra turrax in a 100 mL cylinder for two minutes. After homogenization, distilled water was added to the homogenate to a volume of 50 mL, and the homogenate was filtered with filter paper no. 595 $\frac{1}{2}$ (Schleicher & Schuell, GmbH, Dassel, Germany).

10 mL of the clear solution was titrated with 0.21% 2,6-dichlorophenolindophenol (Merc, Darmstadt, Germany). Ascorbic acid content was calculated using formula (3):

$$AA = (\frac{V_{DIP}}{F} \times W) \times D_1, \quad (3)$$

where:

AA = ascorbic acid (mg kg^{-1} FM);
V_{DIP} = titration volume (Ml);
F = titration volume for one mg ascorbic acid (mL mg^{-1} AA);
W = weight of sample;
D_1 = dilution factor.

The factor F was a titration volume of 1 mL of 0.1% standard solution ascorbic acid (Merck, Darmstadt, Germany) in a mixed solution of 1 mL of 2% oxalic acid and 9 mL of distilled water.

2.8. Determination of Sugars

Carbohydrate analyses were performed according to the procedures of Talburt and Smith [29]. For the assessment of reducing sugar content, 10 g of lyophilized sample was placed in a 250 mL bottle, and 150 mL of distilled water was then added and shaken vigorously. One milliliter of the filtrate was mixed with 3 mL of DNP reagent in a test tube and then heated in a water bath at 95 °C for 6 min. The absorbance of the mixture was measured using a spectrophotometer at a wavelength of 600 nm. The reducing sugar content was then estimated using the standard curve of glucose. The total soluble carbohydrate was determined after the hydrolysis of sugars. After filtration, 40 mL of the filtrate was taken, and two drops of concentrated HCl were added. The samples were warmed for 30 min in a water bath. After cooling, the mixture was neutralized using concentrated NaOH to pH 8. Next, 1 mL of the filtrate was mixed with 3 mL of DNP reagent, and we proceeded according to the procedure for determining the content of reducing sugars. The saccharose content was calculated according to formula (4) [30]:

$$\%\ \text{saccharose} = (\%\ \text{total sugars} - \%\ \text{reducing sugars}) \times 0.95, \quad (4)$$

2.9. Determination of Chlorogenic Acid

Chlorogenic acid was determined spectrophotometrically according to Griffiths, et al. [31]. Freeze-dried potato flour (100 mg) was suspended in 2 mL solution consisting of 0.17 M of Urea (Merck, Darmstadt, Germany) and 0.1 M of acetic acid (Merck, Darmstadt, Germany). After adding 1 mL of distilled water, the suspension was shaken for 15 s. After shaking, 1 mL of 0.014 M natrium nitrate (Merck, Darmstadt, Germany) was added and mixed well. After two minutes of reaction, 1 mL of 0.5 M natriumhydroxid (Carl-Roth, Karlsruhe, Germany) was added to the suspension. The suspension was then centrifuged at 2250× *g* in a centrifuge for 10 minutes. The absorbance of the clear solution was measured at 510 nm with a spectrophotometer (UV-1800 Spectrophotometer System, Shimadzu, Kyoto, Japan). The concentration was calculated from the standard curve produced by measuring 50 ppm to 400 ppm of caffeic acid (Sigma-Aldrich, Darmstadt, Germany).

2.10. Determination of Total Polyphenols

Total phenolic content was determined using the Folin-Ciocalteu reagent (Sigma-Aldrich, Darmstadt, Germany) according to the method of Singleton and Orthofer [32]. A volume of 0.5 mL of Folin-Ciocalteu reagent previously diluted with distilled water (1:10) was mixed with 0.1 mL of each sample. The solution was allowed to stand for 5 min at 25 °C before adding 1.7 mL of sodium carbonate solution (20%). Then, 10 mL of distilled water was added to the mixture and the absorbance was measured at λ = 735 nm after 20 min of incubation with agitation at room temperature. Results were expressed in mg of gallic acid equivalents (GAE) per kg of fresh sample.

2.11. Determination of the Antioxidant Capacity (FRAP)

The determination of the antioxidant capacity by the FRAP method was conducted using the method developed by Benzie and Strein [33]. Immediately prior to the assay, a FRAP working solution was prepared. In total, 250 mL of acetate buffer with a pH of 3.6 (Sigma-Aldrich, Darmstadt, Germany), 25 mL of the TPTZ solution (2,4,6-Tri(2-pyridyl)-s-triazine (Sigma-Aldrich, Darmstadt, Germany) (10 millimoles in 40 mmol HCl) and 25 mL of an iron(III) chloride hexahydrate solution (20 mmol) were mixed (Sigma-Aldrich, Darmstadt, Germany). The solution was incubated at 37 °C, and assays were then performed. Six milliliters of the FRAP solution was taken, and 200 µL of the sample and 600 µL of H_2O were added to it. After 4 min from the addition of the sample, absorbance was measured at a wavelength of 593 nm. Based on the conducted measurements, a curve of dependence of the absorbance value on the juice concentration was plotted. Based on the curve, the absorbance value was determined at a concentration equal to the mean of the dilutions used, and the antioxidant capacity was calculated at the same absorbance value based in the standard curve determined for Fe^{2+} iron ions. In order to remove solids, the samples prior to the assays were centrifuged for 5 min on a Rotina 420R centrifuge (Hettich, Vlotho, Germany) at 3000 revs min^{-1}.

2.12. Statistical Analysis

Field experiments were established in three successive years, 2011, 2012 and 2013, in a completely randomized design (CRD) with four replications. The samples were taken just after harvest and after storage for six months. Quality assessment in each year was performed just after harvest and after storage. The results were statistically analyzed, performing an analysis of variance (ANOVA) of data from each experiment and the synthesis from three years in the mixed model. In the case of significant differences, a Tukey post hoc test was employed with a significance level of $p \leq 0.05$. All analyses were calculated using Statistica® 13.1 software. Correlation coefficients were determined between bioactive compounds and antioxidant capacity using the Pearson coefficient at $p \leq 0.01$ when results were normally distributed.

3. Results and Discussion

This study showed that irrigation had a significant positive effect on the content of all tested nutrients and bioactive compounds, as well as on the antioxidant capacity of potato tubers (Tables 1–10).

Table 1. Dry matter content (%) in "Augusta" potato tubers depending on irrigation, nitrogen fertilization after harvest and long-term storage. Mean for three years of study (2011–2013).

Irrigation (I)	Nitrogen Fertilization (II)	After Harvest	After Storage	Difference [1]
Without irrigation (Control)	Broadcasting	20.6	20.1	−2.43
	Fertigation	21.5	20.5	−4.88
Drip irrigation	Broadcasting	21.8	21.0	−3.68
	Fertigation	21.0	20.4	−2.86
Average for control		21.05	20.25	−3.69
Average for drip irrigation		21.40	20.65	−3.28
Average for broadcasting		21.20	20.55	−3.07
Average for fertigation		21.25	20.45	−3.89
$LSD_{p \leq 0.05}$ Irrigation (I)		0.318	0.159	
$LSD_{p \leq 0.05}$ Nitrogen fertilization (II)		NS	NS	
$LSD_{p \leq 0.05}$ I × II		0.459	0.229	

NS—not significant; [1] Averaged across after harvest = 100% and difference after storage are more (+) or less (−) compared to post-harvest value.

Table 2. Starch concentration (%) in "Augusta" potato tubers depending on irrigation, nitrogen fertilization after harvest and long-term storage. Mean for three years of study (2011–2013).

Irrigation (I)	Nitrogen Fertilization (II)	After Harvest	After Storage	Difference
Without irrigation (Control)	Broadcasting	12.1	11.65	−3.32
	Fertigation	12.7	12.05	−4.74
Drip irrigation	Broadcasting	13.0	12.50	−3.85
	Fertigation	12.5	12.05	−3.21
Average for control		12.40	11.85	−4.05
Average for drip irrigation		12.85	12.28	−3.54
Average for broadcasting		12.55	12.08	−3.59
Average for fertigation		12.75	12.05	−3.98
$LSD_{p \leq 0.05}$ Irrigation (I)		0.342	NS	
$LSD_{p \leq 0.05}$ Nitrogen fertilization (II)		NS	NS	
$LSD_{p \leq 0.05}$ I × II		0.506	0.908	

Explanation in Table 1.

Table 3. Ascorbic acid concentration (mg kg^{-1}) in "Augusta" potato tubers depending on irrigation, nitrogen fertilization and cultivar after harvest and long-term storage. Mean for 2011–2013.

Irrigation (I)	Nitrogen Fertilization (II)	After Harvest	After Storage	Difference
Without irrigation (Control)	Broadcasting	215	159	−25.4
	Fertigation	218	153	−28.8
Drip irrigation	Broadcasting	221	163	−25.3
	Fertigation	228	167	−25.2
Average for control		216.5	156.0	−27.1
Average for drip irrigation		224.5	165.0	−25.2
Average for broadcasting		218.0	161.0	−25.3
Average for fertigation		223.0	160.0	−27.0
$LSD_{p \leq 0.05}$ Irrigation (I)		0.286	0.318	
$LSD_{p \leq 0.05}$ Nitrogen fertilization (II)		0.151	NS	
$LSD_{p \leq 0.05}$ I × II		NS	NS	

Explanation in Table 1.

Table 4. Monosaccharide concentration (g kg^{-1} FM) in "Augusta" potato tubers depending on irrigation, nitrogen fertilization and cultivar after harvest and long-term storage. Mean for 2011–2013.

Irrigation (I)	Nitrogen Fertilization (II)	After Harvest	After Storage	Difference
Without irrigation (Control)	Broadcasting	1.25	3.13	+150
	Fertigation	1.31	3.30	+151
Drip irrigation	Broadcasting	0.93	2.86	+207
	Fertigation	0.90	2.82	+213
Average for control		1.28	3.21	+151
Average for drip irrigation		0.91	2.84	+210
Average for broadcasting		1.09	3.00	+179
Average for fertigation		1.10	3.06	+183
$LSD_{p \leq 0.05}$ Irrigation (I)		0.032	0.021	
$LSD_{p \leq 0.05}$ Nitrogen fertilization (II)		NS	NS	
$LSD_{p \leq 0.05}$ I × II		0.041	NS	

Explanation in Table 1.

Table 5. Saccharose concentration (g kg^{-1} FM) in "Augusta" potato tubers depending on irrigation, nitrogen fertilization and cultivar after harvest and long-term storage. Mean for 2011–2013.

Irrigation (I)	Nitrogen Fertilization (II)	After Harvest	After Storage	Difference
Without irrigation (Control)	Broadcasting	5.94	6.06	+2.1
	Fertigation	6.49	6.21	–4.2
Drip irrigation	Broadcasting	7.59	6.98	−8.0
	Fertigation	7.11	6.86	−3.5
Average for control		6.21	6.14	−1.1
Average for drip irrigation		7.35	6.92	−5.7
Average for broadcasting		6.76	6.52	−3.0
Average for fertigation		6.80	6.54	−3.9
$LSD_{p \leq 0.05}$ Irrigation (I)		0.222	0.286	
$LSD_{p \leq 0.05}$ Nitrogen fertilization (II)		NS	NS	
$LSD_{p \leq 0.05}$ I × II		0.214	NS	

Explanation in Table 1.

Table 6. Total sugar concentrations (g kg^{-1} FM) in "Augusta"potato tubers depending on irrigation. nitrogen fertilization and cultivar after harvest and long-term storage. Mean for 2011–2013.

Irrigation (I)	Nitrogen Fertilization (II)	After Harvest	After Storage	Difference
Without irrigation (Control)	Broadcasting	7.50	9.51	+26.8
	Fertigation	8.14	9.84	+20.9
Drip irrigation	Broadcasting	8.92	10.21	+14.5
	Fertigation	8.38	10.04	+19.8
Average for control		7.82	9.68	+23.7
Average for drip irrigation		8.65	10.12	+17.1
Average for broadcasting		8.21	9.86	+20.1
Average for fertigation		8.26	9.94	+20.3
$LSD_{p \leq 0.05}$ Irrigation (I)		0.159	0.032	
$LSD_{p \leq 0.05}$ Nitrogen fertilization (II)		NS	NS	
$LSD_{p \leq 0.05}$ I × II		0.151	0.133	

Explanation in Table 1.

Table 7. Total polyphenol concentration (mg GAE kg^{-1} FM) in "Augusta" potato tubers depending on irrigation, nitrogen fertilization and cultivar after harvest and long-term storage. Mean for 2011–2013.

Irrigation (I)	Nitrogen Fertilization (II)	After Harvest	After Storage	Difference
Without irrigation (Control)	Broadcasting	181.3	102.3	−43.6
	Fertigation	186.3	111.5	−40.2
Drip irrigation	Broadcasting	169.4	103.4	−39.0
	Fertigation	175.8	106.1	−39.6
Average for control		183.8	106.9	−41.8
Average for drip irrigation		172.6	104.8	−39.3
Average for broadcasting		175.4	102.9	−41.3
Average for fertigation		181.1	108.8	−39.9
$LSD_{p \leq 0.05}$ Irrigation (I)		0.102	0.318	
$LSD_{p \leq 0.05}$ Nitrogen fertilization (II)		0.304	0.444	
$LSD_{p \leq 0.05}$ I × II		0.304	0.506	

Explanation in Table 1.

Table 8. Chlorogenic acid concentration (g kg^{-1} FM) in "Augusta" potato tubers depending on irrigation, nitrogen fertilization and cultivar after harvest and long-term storage. Mean for 2011–2013.

Irrigation (I)	Nitrogen Fertilization (II)	After Harvest	After Storage	Difference
Without irrigation (Control)	Broadcasting	148.5	98.6	−33.6
	Fertigation	151.6	100.4	−33.8
Drip irrigation	Broadcasting	139.2	94.1	−32.4
	Fertigation	146.3	90.3	−38.3
Average for control		150.0	106.9	−33.7
Average for drip irrigation		142.7	104.8	−35.4
Average for broadcasting		143.8	102.9	−33.0
Average for fertigation		148.9	108.8	−36.0
$LSD_{p \leq 0.05}$ Irrigation (I)		0.51	1.59	
$LSD_{p \leq 0.05}$ Nitrogen fertilization (II)		0.59	1.69	
$LSD_{p \leq 0.05}$ I × II		0.71	1.52	

Explanation in Table 1.

Table 9. Antioxidant capacity (FRAP) (mmol Fe^{2+} kg^{-1}) in "Augusta"potato tubers in depend on irrigation, nitrogen fertilization and cultivar after harvest and long-term storage. Mean for 2011–2013.

Irrigation (I)	Nitrogen Fertilization (II)	After Harvest	After Storage	Difference
Without irrigation (Control)	Broadcasting	7.72	6.21	−19.6
	Fertigation	8.15	6.98	−14.4
Drip irrigation	Broadcasting	9.54	7.54	−21.0
	Fertigation	9.91	7.89	−20.4
Average for control		7.94	6.59	−16.9
Average for drip irrigation		9.72	7.72	−20.7
Average for broadcasting		8.63	6.88	−20.3
Average for fertigation		9.03	7.43	−17.7
$LSD_{p \leq 0.05}$ Irrigation (I)		0.095	0.095	
$LSD_{p \leq 0.05}$ Nitrogen fertilization (II)		0.034	0.039	
$LSD_{p \leq 0.05}$ I × II		0.091	0.091	

Explanation in Table 1.

Table 10. Correlation coefficients between bioactive compounds and antioxidant capacity (FRAP).

Antioxidant Capacity	Ascorbic Acid	Total Polyphenols	Chlorogenic Acid
After harvest	0.87 **	−0.77 **	−0.77 **
After storage	0.64 **	NS	−0.81 **

**—significant at $p \leq 0.01$; NS—not significant.

In studies published by Ierna, et al. [16], it was shown that limiting the water stress of plants leads not only to an increase in yield but also to an improvement in its quality. Shi, et al. [34] found that 40–60% of the applied dose of conventional fertilizer is suitable for the production of potatoes with drip fertigation. Ierna, et al. [16] indicated that a moderate dose of fertilization (100:50:150 N:P_2O_5:K_2O kg ha^{-1}) applied by the drip fertigation method not only ensured a high potato yield but also improved the efficient use of water and fertilizer resources. Our research showed the better quality of potato tubers after the application of drip irrigation and fertigation. This may be due to the improved availability of nutrients for the potato in the root zone [35] and better absorption of water and nutrients in potato drop fertigation [36].

In recent years, increasing attention has been paid to food with bioactive substances that have a beneficial effect on the human body. Now, there is widespread interest in the antioxidant compounds present in various products, particularly in vegetables and fruits.

Such substances include, among others, polyphenolic compounds, including chlorogenic acid. These compounds are characterized by high antioxidant activity, and thus anti-inflammatory, antiviral and anticancer properties. Due to the amount consumed, the potato can therefore be a valuable source of bioactive compounds in the diet.

3.1. Effect of Drip Fertigation with Nitrogen Application on Dry Matter and Starch Content after Harvest and Long-Term Storage

The dry matter content of potato tubers affects the taste and the consistency of raw and processed tubers [16]. In the present study, the amount of dry matter in potato tubers "Augusta" depended on the irrigation applied during plant vegetation; irrigation caused a significant increase (Table 1). On the other hand, the method of supplying fertilization—i.e., fertilization by broadcasting or liquid fertilization (fertigation)—did not significantly affect the dry matter content in potato tubers, both after harvest and storage. The smallest standard deviations from the mean of the study years were recorded with drip irrigation and broadcasting, as well as drip irrigation and fertigation, which proves that, despite changing weather conditions, the dry matter content was similar in each of the study years. The largest amount of dry matter (21.8% after harvest and 21.0% after storage) was found in tubers collected from the drip irrigation and nitrogen fertilization by broadcasting treatment combination, both after harvest and after storage. After storage, the greatest losses of dry matter occurred in tubers collected from plots without irrigation with liquid nitrogen fertilization (4.88 percentage points).

The nutritional value of potato tubers is also determined by the carbohydrate content in the form of easily digestible starch. In its raw state, it is difficult to digest; therefore, it is subjected to a thermal treatment which breaks it down into more easily digestible dextrins containing up to 30 glucose molecules. The starch after cooking the tubers determines the taste and texture of the tubers. The starch concentration in tubers in the experiment was significantly increased by drip irrigation (Table 2), but most starch was found in tubers from the drip irrigation and fertilization by broadcasting treatment (13.0%). Similar standard deviations in years were obtained as in the case of dry matter. The greatest losses of starch content during storage, as dry matter, were observed in tubers subjected to fertigation without irrigation. According to the research reported by Świetlikowska [37] and Adamicki and Czerko [38], starch losses during storage result from the conversion of this complex carbohydrate into reducing sugars as a result of the respiration process, thus adversely affecting potato tubers.

3.2. Effect of Drip Fertigation with Nitrogen Application on Ascorbic Acid Concentration after Harvest and Long-Term Storage

Ascorbic acid (vitamin C) is a very potent antioxidant that is soluble in water and also plays an important role in neutralizing the activity of free radicals, which are formed mainly during frying, smoking and storage. Potato antioxidants can be used in the treatment of neoplastic diseases, inflammations and pain, as well as in the treatment of bacterial and viral diseases [17,39–41]. In the present study, potato tubers from irrigated plots contained significantly more vitamin C than tubers collected from control plots (Table 3). The method of nitrogen fertilization in the liquid form significantly increased the concentration of vitamin C in tubers. Unfortunately, the greatest losses of vitamin C after storage, at the level of 28.8 percentage points, occurred in tubers that had just been subjected to fertigation without irrigation.

3.3. Effect of Drip Fertigation with Nitrogen Application on Monosaccharides, Saccharose and Total Sugar Concentration after Harvest and Long-Term Storage

The main sugars present in potato tubers are sucrose, glucose and fructose [41], the concentrations of which depends on the genotype, environmental factors and storage conditions [42–44]. With an increased content of total sugars to approximately 1%, the tubers acquire a sweet taste. Potatoes containing higher amounts of reducing sugars undergo non-enzymatic browning during heating as a result of the Maillard reaction [40,42].

There is an accumulation of starch in tubers during the tuberization phase [36]. As a result, the highest levels of sucrose, glucose and fructose are recorded in young or immature tubers [45], and with physiological maturity, these concentrations tend to decrease [46]. Some studies report values from 0.2% to 1.5% of sucrose and from 0.01% to 0.7% of reducing sugars in immature tubers [47,48], while in the period of physiological maturity, values from 0.1% to 0.6% of sucrose and from 0.04% to 0.4% of reducing sugars have been found [47–49]. In the present research, the concentration of monosaccharides in "Augusta" potato tubers analyzed after harvest ranged from 0.09% to 0.13%, with concentrations of sucrose from 0.59% to 0.76% and total sugars from 0.75% to 0.89%, and these significantly depended on irrigation and on the interaction of irrigation and the method of nitrogen fertilization (Tables 4 and 5). Lower values of monosaccharides and higher values of sucrose and total sugars were recorded after the combined use of drip irrigation and fertigation.

After storage, the concentration of monosaccharides more than doubled in irrigated tubers, while 1.5 times more monosaccharides were evident in non-irrigated tubers. The sucrose concentration was higher in tubers collected from not-irrigated plots with the use of fertilization by broadcasting. In other cases, it was slightly lower in tubers stored for 6 months than the tubers tested immediately after harvest.

The concentration of total sugars after storage increased on average from 14.5% to 26.8% (Table 6). This increase may be caused by the transformation of starch during storage into less complex sugars [37,38].

3.4. Effect of Drip Fertigation with Nitrogen Application on Total Polyphenols and Chlorogenic Acid Concentration after Harvest and Long-Term Storage

Phenolic compounds are the dominant antioxidants in food, and they enhance the action of other antioxidants by protecting vitamin C and β-carotene and contributing to the enhancement of vitamin E [50]. The main phenolic compound of potatoes (chlorogenic acid) is not resistant to thermal treatment. During cooking, it declines to about 65%, while baking destroys it completely. In the potato plant, phenolic compounds play a major role in resistance to disease, inhibiting the action of many pathogens and transforming into suberin, which is deposited in the cell walls of the damaged tuber, acting as a barrier against pathogens [51,52]. In the current research, the total polyphenol content in "Augusta" potato tubers depended on irrigation, fertilization method and the interaction of both factors (Table 7). Most polyphenols were contained in tubers collected from the not-irrigated control plots with fertigation (186.3 mg GAE kg^{-1} FM).

A higher concentration of total phenols may be the result of lower water availability and an increased content of defense phenolic compounds under stress conditions [42]. Grudzińska and Zgórska [53] reported that the storage time did not significantly affect the changes of the studied parameter in the plant material. In the present research it was found that the 6 month storage period of tubers resulted in a decrease in the total polyphenolic compound content. The highest losses of these compounds, amounting to 43.6%, were found in tubers that were not irrigated with the use of fertilization by broadcasting.

According to Ezekiel, et al. [54], Gawlik-Dziki [55] and Rytel, et al. [56], chlorogenic acid and its isomers (crypto-, neo- and isochlorogenic) predominate in the amounts of phenolic acids in potatoes and amount to about 90% of the total phenolics content in tubers, and the remaining acids—caffeic, coumarinic, ferulic and sinapinic acid—are present in small amounts. In the present research, irrigation significantly reduced the content of chlorogenic acid in potato tubers, while the use of fertigation increased the tested compound in tubers tested after harvest (Table 8). After storage, in irrigated and fertigation tubers, the greatest losses of chlorogenic acid (38.3%) were recorded compared to other combinations of the tested factors.

3.5. Effect of Drip Fertigation with Nitrogen Application on Antioxidant Capacity (FRAP) after Harvest and Long-Term Storage

Taking into account the antioxidant capacity (FRAP), significantly higher antioxidant properties of "Augusta" potato tubers irrigated with fertigation were found, both imme-

diately after harvest and after storage (Table 9). The content of ascorbic acid significantly positively influenced the antioxidant capacity, causing it to increase, while the content of polyphenols and chlorogenic acid had a significant negative effect, causing it to decrease (Table 10). This could be because ascorbic acid contributes more to the antioxidant capacity than phenolic compounds. The greater amounts of phenolic compounds, including chlorogenic acid, in non-irrigated tubers could be caused by stress due to the lack of water availability, which, however, had a negative effect on the synthesis of ascorbic acid and the antioxidant capacity of tubers in the studies by Lombardo et al. [57], as the synthesis of phenolic compounds is associated with the host's defense response to biotic and abiotic stress. The growing environment has a large impact on the content of polyphenols in a given plant tissue, but it is also genetically determined.

4. Conclusions

Due to the quantity and regularity of potato consumption, potatoes can be a valuable source of antioxidants in the human diet. Current research on the influence of drip irrigation and nitrogen fertilization by fertigation or broadcasting on the content of nutrients and bioactive compounds in "Augusta" potato tubers showed that drip irrigation had a positive effect on the level of the tested components. The interactive effect of drip irrigation and broadcasting increased the concentration of dry matter and starch, saccharose and total sugars. In turn, the combined effect of drip irrigation and fertigation decreased the concentration of monosaccharides. The use of liquid nitrogen fertilization (fertigation) significantly increased the content of bioactive compounds such as vitamin C, total polyphenols and chlorogenic acid, as well as the antioxidant activity of potato tubers. However, the long-term storage period (6 months) resulted in losses of the measured components, with the exception of the content of monosaccharides, where a more than twofold increase was recorded, especially in irrigated tubers. This change could be caused by the transformation of starch to monosaccharides. Taken together, the presented studies make an important contribution to the knowledge of planning potato cultivation with good nutritional value and a high content of bioactive components using drip irrigation. The present research also makes it possible to choose the most effective method of nitrogen fertilization for the cultivation of high-value potato tubers. Therefore, the results of the study can be very useful from a practical point of view. Under the conditions of drip fertigation, a higher efficiency of water and nutrient use was obtained, which is confirmed by the results of research on the most important nutrients and bioactive compounds in potato tubers.

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