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Effects of Supplemental Irrigation and Hydrogel Application on the Enzymatic Darkening Susceptibility of Potato Tubers After Harvest and Storage

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Abstract

Increasing drought frequency associated with climate change highlights the need for effective water management to maintain potato tuber quality during production and storage. This study evaluated the effects of growing-season conditions, cultivar, supplemental irrigation, and hydrogel application on tuber oxidative potential and chlorogenic, ascorbic, and citric acid contents at harvest and after six months of storage. A three-year field experiment (2020–2022) was conducted using ten potato (*Solanum tuberosum* L.) cultivars under three cultivation treatments: control, supplemental irrigation, and hydrogel application. The year of the experiment, reflecting weather conditions during the growing season, was the factor that most strongly determined the analyzed quality parameters. The mean blackspot index was lowest in 2020 (0.207 AU475) and highest in 2021 (0.568 AU475), demonstrating substantial seasonal variation. Cultivar effects were also evident, with the highest mean values recorded for Bohun (0.449 AU475), Baltic Fire (0.418 AU475), Tajfun (0.416 AU475), and American Rose (0.415 AU475), whereas Ismena and Golden Marie had the lowest values (0.304 and 0.312 AU475, respectively). Chlorogenic acid was strongly positively correlated with oxidative potential (Spearman's $r = 0.757$ – 0.852), whereas ascorbic and citric acids showed opposite associations. Both supplemental irrigation and hydrogel reduced susceptibility to enzymatic browning, but their effectiveness depended on growing-season conditions. Hydrogel application was most effective under the greatest water deficit, whereas its effect was less pronounced in wetter seasons. Overall, the results demonstrate that weather conditions during the growing season were the primary determinant of tuber quality, while cultivar and water-management practices modified the response. Hydrogel application may therefore provide a useful strategy for reducing drought-related quality deterioration and improving the storage stability of potato tubers under water-limited conditions.



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1. Introduction

Potato (*Solanum tuberosum* L.) is one of the world's most important food crops and plays a crucial role in ensuring global food security [1–3]. Apart from yield capacity and nutritional value, the commercial value of potato tubers is largely determined by their visual quality [4,5]. Appearance, texture, and resistance to post-peeling and post-cutting discoloration represent key traits driving consumer preferences and raw material suitability for

industrial processing [4,6,7]. Enzymatic browning remains one of the most critical economic challenges, particularly regarding fresh-cut and processed potato products. Discoloration impairs perceived freshness, technological quality, and market appeal [5,8,9]. Enzymatic browning in potato tissues primarily results from polyphenol oxidase (PPO) activity, which catalyzes two key reactions: the hydroxylation of monophenols to o-diphenols and the oxidation of o-diphenols to o-quinones [10]. The resulting o-quinones are highly reactive molecules that undergo polymerization and condensation with amino acids, proteins, and sugars, leading to the formation of brown, melanin-like pigments. The enzymatic activity of PPO and peroxidase (POD) is initiated primarily after mechanical tissue damage—such as during peeling, slicing, or shredding—when cell disruption enables contact between enzymes and phenolic substrates in the presence of oxygen [11]. Furthermore, the intensity and rate of enzymatic browning are influenced by the content of bioactive compounds present in the tubers. Among these compounds, chlorogenic acid is the predominant phenolic compound in potato tubers, accounting for approximately 90% of total phenolics, whereas ascorbic acid is considered the main non-phenolic antioxidant involved in limiting oxidative reactions [12]. Hydrogen peroxide (H_2O_2), generated as a byproduct during PPO-catalyzed phenolic oxidation, can subsequently serve as a substrate for thermostable peroxidase (POD), which oxidizes various secondary substrates and yields dark reaction products [7]. However, tuber susceptibility to discoloration does not depend exclusively on phenolic content. The oxidative potential of potato tissues depends on the balance between oxidative processes and the endogenous antioxidant system [12,13]. Prominent natural antioxidants in potato tubers include ascorbic acid and citric acid. Among these, ascorbic acid plays a pivotal role in suppressing enzymatic browning primarily by reducing generated o-quinones back to their parent phenolic substrates, thereby preventing the formation of melanin pigments. At higher concentrations, it may also function as a competitive inhibitor of PPO; nevertheless, its primary anti-browning effect stems from its strong antioxidant potential and its ability to reduce PPO-catalyzed oxidation products [14,15]. Citric acid, on the other hand, exerts an indirect effect by lowering pH and chelating metal ions essential for PPO enzymatic activity [16,17]. Therefore, the oxidative potential of potato tubers reflects the complex interaction between chlorogenic, ascorbic, and citric acids and the activities of oxidative enzymes.

The metabolic profile of potato tubers is strongly influenced by environmental conditions prevailing throughout the growing season [18]. Water availability represents one of the key factors affecting plant physiology and secondary metabolism pathways [19]. Periods of water deficit can induce oxidative stress and modify the biosynthesis of phenolic compounds, which constitute an important component of plant defense mechanisms [12,20,21]. In numerous plant species, drought stress has been associated with increased accumulation of phenolic compounds, particularly chlorogenic acid, accompanied by changes in vitamin C and organic acid concentrations. Water deficiency activates the phenylpropanoid pathway and enhances the activity of key enzymes, such as phenylalanine ammonia-lyase (PAL), thereby stimulating the synthesis of secondary metabolites with antioxidant properties. Simultaneously, alterations in vitamin C and organic acid levels contribute to changes in the overall oxidative status of plant tissues [22,23].

In the context of ongoing climate change, irregular precipitation patterns and increasing frequency of drought events represent significant challenges for global potato production [24,25]. Therefore, agrotechnological strategies aimed at improving soil water retention and maintaining stable crop water availability are becoming increasingly important [26–28]. Supplemental irrigation is considered one of the most effective practices for mitigating short-term water deficits, positively affecting root development, photosynthetic activity, biomass production, and marketable tuber yield [29,30].

In addition, drought mitigation strategies increasingly involve the use of soil amendments such as hydrogels—superabsorbent polymers capable of retaining large amounts of water—which improve soil water-holding capacity [31]. The application of hydrogels combined with optimized irrigation management can enhance tuber yield, improve plant biometric parameters, and increase water-use efficiency (WUE), particularly under water-limited conditions [32]. By increasing plant-available water in the rhizosphere, hydrogels can alleviate physiological stress and influence subsequent metabolic responses in plants.

In the context of postharvest quality management in potatoes, chemical and physiological alterations occurring not only during the growing season but also throughout storage play a decisive role. Storage represents a critical stage in the production chain, influencing the stability of chemical composition and functional properties of potato tubers. Prolonged storage induces significant changes in metabolic profiles that affect the oxidative potential of tuber tissues. Previous studies have demonstrated that extended storage may lead to an accumulation of chlorogenic acid, which is associated with enhanced phenolic oxidation and increased susceptibility to enzymatic browning [12,13,33]. Simultaneously, a progressive decline in ascorbic acid content has been observed, reducing the capacity to neutralize generated o -quinones and weakening tissue antioxidant protection [12]. Conversely, citric acid contributes to redox balance by chelating transition metal ions and modulating the activity of oxidative enzymes, thereby indirectly affecting PPO-catalyzed reactions [16,34]. Consequently, these metabolic changes may shift the physiological balance toward pro-oxidative processes, increasing overall tissue oxidative potential and susceptibility to flesh discoloration.

Despite extensive research on the effects of irrigation and soil amendments on yield and basic nutritional quality parameters, their combined effects on oxidative potential and susceptibility to enzymatic browning remain insufficiently characterized. In particular, limited information is available regarding the interactive influence of these agrotechnological practices on oxidative–antioxidant balance and the biochemical mechanisms determining browning intensity both after harvest and during long-term storage [27,30,31]. Considering the important role of phenolic compounds and organic acids in discoloration processes, understanding these relationships may contribute to the development of field management strategies aimed at producing potato tubers with improved commercial and processing quality.

The objective of this study was to evaluate the oxidative potential of potato tubers, with particular emphasis on changes in chlorogenic, ascorbic, and citric acid contents, under different water management strategies across diverse potato cultivars, both at harvest and after long-term storage. The findings provide insights into the influence of targeted water management practices on postharvest tuber stability and may support the development of sustainable agrotechnological approaches under changing climate conditions.

2. Materials and Methods

2.1. Plant Material and Field Experiment

The study was conducted over three growing seasons (2020–2022) at the Agricultural Experimental Station in Minikowo (53°10′02″ N, 17°44′22″ E), operated by the Bydgoszcz University of Science and Technology, in the Kuyavian–Pomeranian region of Poland. The experiment was established on lessive soil (lessive podzolic type, soil quality class IIIa, very good rye complex). Prior to the trial, baseline soil properties included a pH (in 1 M KCl) of 4.7 and available nutrient contents of 7.1 mg P₂O₅, 17.1 mg K₂O, and 4.5 mg MgO per 100 g of soil. Cereals were grown as the preceding crop.

The analyzed cultivars were: American Rose, Baltic Fire, Bohun, Gardena, Golden Marie, Impresja, Ismena, Mia, Tacja, Tajfun. The cultivars were selected to represent

variation in phenotypic traits, productivity, and potential technological and nutritional value. Based on their maturity group, the tested cultivars were classified as very early (Impresja and Tacja), medium-early (Baltic Fire, Bohun, Gardena, Golden Marie, Ismena, and Mia), and medium-late (American Rose and Tajfun). This classification is based on the length of the growing season of the cultivars studied. According to the current National Potato Register in Poland, early and medium-early cultivars constitute the largest group. Tubers were harvested at full technological maturity from experimental plots. The cultivars originated from three breeding companies: Hodowla Ziemniaka Zamarte Sp. z o.o. (part of the IHAR Group—Institute of Plant Breeding and Acclimatization) in Zamarte, Pomorsko-Mazurska Hodowla Ziemniaka in Strzeżecin, and Norika Polska Sp. z o.o., the sole representative of the German company Norika Nordring Kartoffelzucht und Vermehrungs GmbH based in Barlinek. Specifically, cultivars from Hodowla Zamarte included Bohun, Gardena, Impresja, Tacja, and Ismena; cultivars from Pomorsko-Mazurska Hodowla included Tajfun; while cultivars from Norika included American Rose, Baltic Fire, Golden Marie, and Mia.

The experiment followed a randomized complete block design with three replications. Each experimental plot covered 30 m², with plants spaced 0.30 m within rows and 0.75 m between rows. Planting was carried out annually on 30 April.

For each cultivar, three cultivation treatments were applied:

1. Control (C)—standard cultivation without additional measures aimed at improving soil water retention,
2. Supplemental irrigation (I)—irrigation applied during periods of water deficit according to crop requirements. The plots were irrigated using a sprinkler irrigation system (H530—HIPODROM IRTEC bridge sprinkler, IRTEC S.p.A., Castelvetro di Modena, Italy). Irrigation scheduling was based on crop water requirements. The total amount of supplemental irrigation water applied during the growing season was approximately 25 mm in 2020, 72 mm in 2021, and 76 mm in 2022. Natural precipitation during the growing seasons was recorded using the Agrometeorological Weather Station in Minikowo and was considered in the assessment of water availability.
3. Hydrogel treatment (H)—the hydrogel was applied before planting at a rate of 30 kg ha⁻¹. The polymer was uniformly distributed in the planting rows and incorporated into the soil within the root zone. The hydrogel (Rolmarket, Torseed S.A., Toruń, Poland) preparation is in the form of granules (0.35–1.10 mm); pH 6–10; 1 g of hydrogel absorbs from 200 to 600 g of water. The material exhibits an annual biodegradability rate of approximately 10–15% in agricultural soils.

No farmyard manure or other organic fertilizers were applied during the experiment. Mineral fertilization was based exclusively on mineral fertilizers. Mineral fertilization (YaraMila Viking NPK—YaraInternational ASA, Porsgrunn, Norway): 14% N, 14% P₂O₅, 21% K₂O) was applied before planting at rates of 105 kg N ha⁻¹, 105 kg P₂O₅ ha⁻¹, and 158 kg K₂O ha⁻¹. Foliar micronutrient fertilization was performed at the 3–4 leaf stage using boron—1 L ha⁻¹ (YaraVita Bortrac—YaraInternational ASA, Porsgrunn, Norway, 150 g B L⁻¹), followed by application of YaraVita Kombiphos (YaraInternational ASA, Porsgrunn, Norway)—5 L ha⁻¹ (P₂O₅—440 g L⁻¹ K₂O—75 g L⁻¹, MgO—67 g L⁻¹, CaO—23 g L⁻¹, Mn—10 g L⁻¹, Zn—5 g L⁻¹) at the stage of row closure.

Crop protection practices were conducted according to the principles of integrated pest management (IPM). Weed control included pre-emergence application of Stomp 400 SC (BASFSE, Ludwigshafen, Germany) (active substance: pendimethalin, 400 g L⁻¹) and Aklonifen 600 SC (BayerAG, Leverkusen, Germany) (aclonifen, 600 g L⁻¹) at rates of 3 L ha⁻¹ + 2 L ha⁻¹, respectively, followed by Focus Ultra 100 EC (BASFSE, Ludwigshafen, Germany) (cycloxydim, 100 g L⁻¹; 1 L ha⁻¹) applied with the multifunctional adjuvant

Dash HC (BASFSE, Ludwigshafen, Germany) (methyl oleate, 348.75 g L^{-1} ; fatty alcohol, 209.25 g L^{-1}). Disease control was performed using three fungicide applications during the growing season: the first prior to bud formation using Enervin SC (BASFSE, Ludwigshafen, Germany) (ametotradin, 200 g L^{-1} ; 1.2 L ha^{-1}) combined with Polyram 70 WG (BASFSE, Ludwigshafen, Germany) (metiram, 700 g kg^{-1} ; 1.8 kg ha^{-1}), the second at the budding stage using Cabrio Duo 112 EC (BASFSE, Ludwigshafen, Germany) (dimethomorph, 72 g L^{-1} + pyraclostrobin, 40 g L^{-1} ; 2.5 L ha^{-1}), and the third immediately after flowering using Acrobat MZ 69 WG (BASFSE, Ludwigshafen, Germany) (mancozeb, 600 g kg^{-1} + dimethomorph, 90 g kg^{-1} ; 2 kg ha^{-1}). Insect control was carried out using Mospilan 20 SP (NipponSodaCo., Ltd., Tokyo, Japan) (acetamiprid, 200 g kg^{-1}) at a rate of 0.08 kg ha^{-1} .

Meteorological conditions during the study period are presented in Figure 1, which shows monthly precipitation totals and mean air temperatures from January to December in 2020–2022. Considerable differences in precipitation distribution and temperature were observed among the years. During the potato growing season, particularly high precipitation was recorded in June and August 2020 (165.5 and 104.7 mm , respectively). In contrast, precipitation in these months was substantially lower in 2021 (40.9 and 34.1 mm , respectively). In 2022, precipitation reached 39.5 mm in June and 63.7 mm in August. The highest mean monthly air temperatures occurred in summer, with the peak values observed in July 2021 and August 2022. These differences in temperature and precipitation provided contrasting environmental conditions for potato growth and tuber development. Tubers were harvested at full technological maturity (September–October), depending on the earliness group. At harvest, 10 kg of undamaged, uniform tubers per plot were collected for post-harvest assessment, and an additional 10 kg per plot was collected for storage evaluation (6 months in a storage chamber at $+4 \text{ }^{\circ}\text{C}$ and 95% relative humidity).

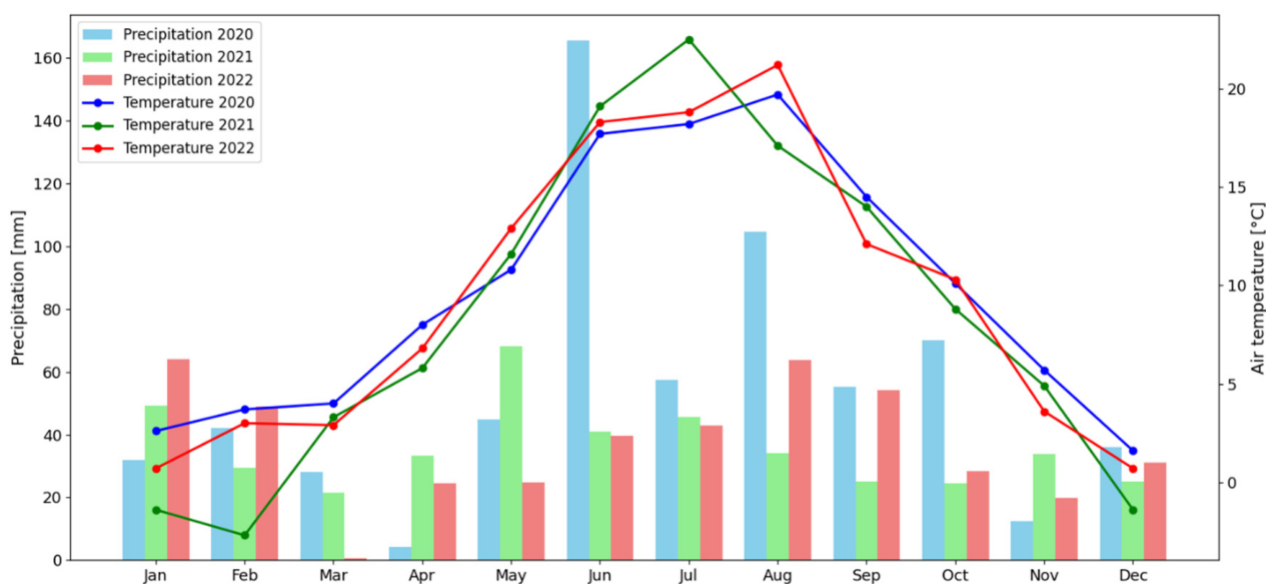


Figure 1. Monthly precipitation totals and mean air temperatures in Minikowo, Poland, in 2020–2022.

For chemical analyses, representative tuber samples were collected independently from each of the three field plots (biological replicates, $n = 3$ per treatment). The selected tubers were washed, air-dried, and cut into $1 \times 1 \times 1 \text{ cm}$ cubes. The material was immediately frozen in liquid nitrogen and stored at $-18 \text{ }^{\circ}\text{C}$ prior to freeze-drying. Samples were subsequently freeze-dried, ground to a particle size of $0.3\text{--}0.5 \text{ mm}$ and kept in airtight containers in a desiccator under dark conditions until analysis. All laboratory chemical determinations were performed in triplicate as technical replicates for each biological sample (experimental

unit). For statistical evaluation (ANOVA), the mean values of these technical triplicates were used, ensuring that the field plot ($n = 3$) served as the true experimental unit.

2.2. Laboratory Analysis Procedure

2.2.1. The Oxidative Potential

The oxidative potential of fresh potato tubers was evaluated spectrophotometrically based on pigment formation after controlled oxidation.

Fresh tubers were cut into smaller pieces representing the entire tuber tissue and homogenized. Representative samples (25 g) of the homogenized material were mixed with 0.02 M phosphate buffer (1:2, w/v) for 180 s using a laboratory blender (BOSCH, model MSM67170, BSH GmbH, Munich, Germany). The homogenate was stored in sealed containers at 20 °C for 24 h in the dark to allow enzymatic oxidation.

Samples were subsequently filtered through Whatman filter paper (International Limited, Kent, UK) and centrifuged at 12,000 rpm using a Rotina 420 R centrifuge (Hettina Zentrifugen, Tuttlingen, Germany). Prior to measurement, extracts were diluted (1:3) with phosphate buffer.

Absorbance was measured at 475 nm using a SHIMADZU UV-1800 spectrophotometer (UV-Vis Spectral Photometer System, Kyoto, Japan). Results were expressed as absorbance units at 475 nm (AU_{475}). All determinations were performed in triplicate.

The assessment of the susceptibility of the tuber flesh to enzymatic browning was carried out based on the classification of tuber susceptibility to browning according to the method of Dean et al. [35]. The susceptibility of potato tubers to enzymatic browning was classified according to Dean et al. [35]. Based on the blackspot index, values of 0.201–0.400 AU_{475} indicate moderate resistance, whereas values of 0.401–0.600 AU_{475} indicate moderate susceptibility.

2.2.2. Determination of Ascorbic Acid

Ascorbic acid was determined spectrophotometrically using the 2,4-dinitrophenylhydrazine (2,4-DNPH) method [36]. Freeze-dried potato material (5 g) was extracted with metaphosphoric acid–acetic acid solution, and the extract was filtered and centrifuged. An aliquot (4 mL) was oxidized with 3% bromine water, after which excess bromine was neutralized with 10% thiourea. The sample was then reacted with 2,4-DNPH and incubated at 37 °C for 3 h. After cooling, chilled 85% sulfuric acid was added. Absorbance was measured at 521 nm using a SHIMADZU UV-1800 spectrophotometer. Ascorbic acid content was calculated from an external calibration curve prepared using analytical-grade ascorbic acid. Analyses were performed in triplicate.

2.2.3. Determination of Chlorogenic Acid

Chlorogenic acid was quantified using a colorimetric assay based on complex formation in alkaline conditions in the presence of sodium nitrate [37].

Approximately 200 mg of freeze-dried potato powder was extracted in 0.17 M urea and 0.10 M acetic acid. Sodium nitrate (0.14 M) and sodium hydroxide (0.5 M) were added, and the mixture was vortexed and allowed to react at room temperature for 2 min.

Samples were centrifuged (2250 rpm, 10 min) using a Rotina 420 R centrifuge (Andreas Hettich GmbH & Co. KG, Tuttlingen, Germany). The absorbance of the supernatant was measured at 510 nm with a SHIMADZU UV-1800 spectrophotometer (UV-Vis Spectral Photometer System, Japan). Chlorogenic acid concentration was calculated using a calibration curve prepared with analytical-grade standards. Determinations were performed in triplicate.

2.2.4. Determination of Citric Acid

Citric acid was determined colorimetrically using acetic anhydride and pyridine [38]. Freeze-dried potato material (5 g) was extracted with distilled water (100 mL) by shaking for 60 min. After filtration, an 8 mL aliquot was treated with 5% trichloroacetic acid and heated at 80 °C for 1 h. The sample was cooled and centrifuged, and 0.5 mL of the supernatant was reacted with acetic anhydride and pyridine. The reaction was carried out at 60 °C, and absorbance was measured at 420 nm against a reagent blank using a SHIMADZU UV-1800 spectrophotometer. Citric acid content was calculated using a calibration curve covering 15–400 mg L⁻¹. All measurements were performed in triplicate.

2.3. Statistical Analysis of the Results

Statistical analyses were performed using Statistica 13.1 software (StatSoft Inc., Tulsa, OK, USA). Prior to analysis, data distribution was assessed for normality using the Shapiro–Wilk test, and homogeneity of variance was verified. To evaluate the overall effects of the experimental factors and their interactions, a three-way analysis of variance (ANOVA) was performed, with Year, Cultivar, and Treatment as main factors, including all two-way and three-way interactions. In addition, because the growing seasons differed markedly in meteorological conditions, treatment effects were analyzed separately for each year. Where appropriate, cultivar-specific comparisons were also conducted. Significant differences between means were determined using Tukey's honestly significant difference (HSD) test at $p \leq 0.05$. Results are presented as means $\pm$ standard deviation (SD).

3. Results and Discussion

3.1. Oxidative Potential

Progressive climate change, including increasing temperatures and irregular precipitation patterns, significantly modifies growing season conditions and intensifies environmental stress in plants [24]. In potato cultivation, these factors affect not only yield performance but also metabolic processes and the level of oxidative stress in tubers [18]. Therefore, variability in weather conditions may substantially determine quality traits associated with enzymatic browning susceptibility and the content of bioactive compounds.

In the three-year field experiment, significant effects of year, cultivar, and applied agrotechnological practices on the blackspot index value were demonstrated. This index reflects the oxidative potential of tubers and their susceptibility to enzymatic discoloration. Among the analyzed factors, the year of study was the strongest determinant of this trait, showing the highest F-value (Table 1). The three-way interaction between year, cultivar, and treatment was not significant (Table 1), indicating that the combined effect of these three factors was not statistically significant for oxidative potential.

Regardless of the analyzed factors, the lowest blackspot value, averaging 0.207 AU₄₇₅, was recorded in 2020, whereas the highest value (0.568 AU₄₇₅) was observed in 2021 (Table 2). The differences in blackspot values were associated with varying meteorological conditions (Figure 1). The year 2020 was characterized by the highest precipitation (557.9 mm annual rainfall), with exceptionally high rainfall in June (165.5 mm), which favored the maintenance of adequate soil moisture during the period of intensive tuber bulking. Stable water availability limited oxidative stress and reduced tissue susceptibility to mechanical damage and, consequently, enzymatic browning of tubers.

Table 1. Three-factor ANOVA results for blackspot (AU₄₇₅) and the contents of chlorogenic, ascorbic, and citric acids in potato tubers.

Source	df	SS	MS	F	p	Sig.
Oxidative potential [AU ₄₇₅]						
Year	2	1.441	0.7205	5203.9	<0.001	***
Cultivar	9	0.6235	0.0693	500.4	<0.001	***
Treatment	2	0.1704	0.0852	615.3	<0.001	***
Year × Cultivar	18	0.0205	0.0011	8.21	<0.001	***
Year × Treatment	4	0.0354	0.0088	63.85	<0.001	***
Cultivar × Treatment	18	0.016	0.0009	6.43	<0.001	***
Cultivar × Treatment × Year	36	0.002	0.00005	0.4	0.351	n.s.
Residual	180	0.024	0.00014			
Chlorogenic acid						
Year	2	772,313	386,156	5032.8	<0.001	***
Cultivar	9	87,823	9758	127.2	<0.001	***
Treatment	2	70,537	35,269	459.7	<0.001	***
Year × Cultivar	18	5556	309	4.0	<0.001	***
Year × Treatment	4	9859	2465	32.1	<0.001	***
Cultivar × Treatment	18	3207	178	2.3	0.003	***
Cultivar × Treatment × Year	36	3123	87	1.13	0.300	n.s.
Residual	180	13,811	77			
Ascorbic acid						
Year	2	223,220	111,610	3966.6	<0.001	***
Cultivar	9	28,828	3203	113.8	<0.001	***
Treatment	2	3917	1958	69.6	<0.001	***
Year × Cultivar	18	1783	99	3.5	<0.001	***
Year × Treatment	4	3380	845	30.0	<0.001	***
Cultivar × Treatment	18	588	33	1.2	0.299	n.s.
Cultivar × Treatment × Year	36	1113	31	1.1	0.335	n.s.
Residual	180	5065	28			
Citric acid						
Year	2	1,586,665	793,332	10,059.5	<0.001	***
Cultivar	9	55,636	6182	78.4	<0.001	***
Treatment	2	7877	3938	49.9	<0.001	***
Year × Cultivar	18	1312	73	0.9	0.550	n.s.
Year × Treatment	4	22,329	5582	70.8	<0.001	***
Cultivar × Treatment	18	4366	243	3.1	<0.001	***
Cultivar × Treatment × Year	36	893	25	0.3	0.999	n.s.
Residual	180	14,196	79			

df—Degrees of Freedom, SS—Sum of Squares, MS—Mean Square, F—F-statistic, n.s.—not significant, Sig.—Significance: *** $p < 0.001$.

In contrast, 2021 was characterized by lower precipitation (430.4 mm) and higher average temperatures, with particularly high temperatures recorded in July (22.5 °C). These conditions promoted the occurrence of water stress, resulting in a marked increase in tuber susceptibility to browning. This observation is consistent with the findings of Wszelaczyńska et al. [12], who demonstrated that weather conditions significantly affect the oxidative potential of potato tubers. These authors emphasized that lower annual precipitation and periods of elevated temperatures during the growing season increase tuber oxidative potential, thereby enhancing flesh susceptibility to discoloration.

Table 2. Chlorogenic acid, ascorbic acid, and citric acid depending on the cultivar. (CL—cultivar; T—treatment; C—control; I—supplemental irrigation; H—hydrogel).

CL	T	CHLOROGENIC ACID [mg kg ^{−1} f.m.]			ASCORBIC ACID [mg kg ^{−1} f.m.]			CITRIC ACID [mg kg ^{−1} f.m.]		
		2020	2021	2022	2020	2021	2022	2020	2021	2022
AMERICAN ROSE	C	221.8 ± 1.7 a	369.7 ± 2.9 b	287.4 ± 2.3 b	218.2 ± 1.2 b	195.1 ± 0.8 b	236.8 ± 0.3 b	446.4 ± 2.2 a	167.4 ± 1.3 b	341.6 ± 1.7 a
	I	219.3 ± 5.6 a	339.3 ± 8.6 a	273.3 ± 7.0 b	225.6 ± 0.6 c	201.5 ± 1.2 c	244.6 ± 1.0 c	448.5 ± 20.6 a	172.9 ± 11.9 c	388.2 ± 9.9 b
	H	211.8 ± 6.0 a	331.8 ± 9.4 a	253.3 ± 7.2 a	206.8 ± 0.9 a	185.4 ± 1.0 a	226.9 ± 1.1 a	459.9 ± 5.7 a	185.1 ± 3.4 a	360.7 ± 6.2 ab
	MEAN	217.6BC	346.9ABC	271.3ABC	216.9BC	194.0C	236.1BC	451.6BCD	175.1B	363.5BCD
BALTIC FIRE	C	225.5 ± 11.0 a	375.8 ± 4.6 b	292.2 ± 13.1 b	197.1 ± 1.0 a	177.0 ± 1.3 a	214.9 ± 5.5 a	408.3 ± 7.5 a	151.9 ± 4.3 a	312.5 ± 12.0 a
	I	217.9 ± 7.4 a	373.2 ± 7.3 b	271.5 ± 9.3 ab	195.0 ± 3.1 a	187.1 ± 2.4 b	227.8 ± 11.7 b	416.0 ± 13.9 ab	158.6 ± 7.9 a	360.1 ± 7.2 b
	H	210.6 ± 4.7 a	330.0 ± 14.3 a	252.1 ± 9.3 a	208.6 ± 2.1 b	174.6 ± 2.5 a	214.9 ± 0.8 a	437.0 ± 9.1 b	156.7 ± 5.2 a	341.8 ± 3.5 b
	MEAN	218.0BC	359.7CD	271.9ABC	200.2A	179.6A	219.2A	420.4A	155.7A	338.1AB
BOHUN	C	248.8 ± 12.4 a	414.8 ± 6.5 b	322.4 ± 6.0 b	205.8 ± 1.3 ab	184.4 ± 1.0 a	224.6 ± 4.6 a	406.7 ± 4.5 a	158.2 ± 2.5 a	311.3 ± 4.4 a
	I	241.7 ± 3.9 a	398.0 ± 11.9 ab	298.8 ± 1.6 ab	217.2 ± 1.4 b	190.2 ± 2.6 b	245.7 ± 3.8 b	410.3 ± 5.1 a	160.9 ± 2.9 a	355.1 ± 10.4 b
	H	230.6 ± 7.6 a	361.4 ± 18.4 a	275.8 ± 4.1 a	203.7 ± 7.9 a	182.3 ± 2.1 a	225.3 ± 1.0 a	430.8 ± 15.0 b	163.6 ± 8.4 a	336.0 ± 12.7 b
	MEAN	240.4D	391.4D	299.0C	208.9AB	185.6AB	231.9AB	415.9A	160.9A	334.1A
GARDENA	C	230.2 ± 11.0 ab	383.8 ± 5.1 b	298.3 ± 9.1 b	219.2 ± 1.7 a	194.0 ± 1.3 a	236.3 ± 2.7 a	427.5 ± 16.9 a	168.4 ± 9.5 a	327.1 ± 7.3 a
	I	235.0 ± 3.3 b	363.6 ± 6.0 ab	292.8 ± 14 b	226.5 ± 3.2 b	202.1 ± 2.8 b	245.4 ± 2.1 b	422.0 ± 9.7 a	174.0 ± 5.5 a	365.2 ± 13.9 b
	H	214.7 ± 3.8 a	336.4 ± 1.4 a	256.8 ± 4.1 a	214.8 ± 2.5 a	190.0 ± 2.6 a	234.1 ± 2.6 a	430.5 ± 17.7 a	188.9 ± 10.6 b	336.6 ± 3.8 ab
	MEAN	226.6AB	361.2AB	282.3AB	218.2AB	195.3AB	238.6AB	426.4AB	177.1AB	342.9AB

Table 2. Cont.

CL	T	CHLOROGENIC ACID [mg kg ^{−1} f.m.]			ASCORBIC ACID [mg kg ^{−1} f.m.]			CITRIC ACID [mg kg ^{−1} f.m.]		
		2020	2021	2022	2020	2021	2022	2020	2021	2022
	MEAN	226.7CD	361.3CD	282.6BC	220.2BCD	195.4C	238.6BCD	426.6AB	177.1B	343.0ABC
GOLDEN MARIE	C	209.7 ± 0.9 a	349.5 ± 10.4 b	271.6 ± 4.6 b	227.9 ± 2.5 a	202.4 ± 1.9 b	245.7 ± 4.5 a	452.0 ± 4.9 ab	171.3 ± 2.8 a	346.0 ± 4.4 a
	I	203.3 ± 6.8 a	314.5 ± 25.9 ab	252.5 ± 1.2 b	235.8 ± 6.1 a	206.7 ± 0.6 c	255.7 ± 2.2 a	444.5 ± 4.0 a	174.2 ± 2.3 a	383.3 ± 4.1 b
	H	187.3 ± 3.7 a	293.5 ± 6.2 a	210.9 ± 9.0 a	225.7 ± 9.6 a	196.6 ± 1.1 a	245.7 ± 14 a	459.3 ± 7.6 b	180.7 ± 7.2 a	355.1 ± 1.4 a
	MEAN	200.1A	319.2AB	245.0A	229.8CDE	201.9CDE	249.0CDE	451.9BCD	175.4B	361.4ABCD
IMPRESJA	C	216.7 ± 3.7 a	361.3 ± 19.8 b	280.9 ± 18.6 b	232.9 ± 1.5 a	208.8 ± 1.5 a	254.1 ± 1.7 a	477.4 ± 1.9 ab	177.7 ± 1.1 a	365.4 ± 25.0 a
	I	204.1 ± 11.4 a	356.6 ± 8.6 b	256.2 ± 4.8 b	248.6 ± 2.2 b	219.3 ± 5.3 b	271.4 ± 4.5 b	444.7 ± 21.3 a	188.2 ± 7.4 a	380.7 ± 1.3 a
	H	200.0 ± 5.5 a	313.4 ± 3.6 a	239.2 ± 11.3 a	231.5 ± 5.4 a	211.6 ± 1.8 ab	253.7 ± 16.1 a	483.6 ± 13.3 b	191.3 ± 10.0 a	375.6 ± 3.9 a
	MEAN	206.9AB	343.8ABC	258.8AB	237.7E	213.2G	259.7E	468.6D	185.7B	373.9D
ISMENA	C	212.5 ± 2.2 c	354.3 ± 9.3 c	275.4 ± 6.6 c	231.1 ± 0.7 a	207.9 ± 1.1 a	252.4 ± 4.6 a	461.5 ± 5.9 a	177.0 ± 3.4 a	352.8 ± 22.0 a
	I	200.2 ± 5.2 B	308.9 ± 2.6 b	253.5 ± 2.8 b	242.0 ± 4.6 b	215.4 ± 2.7 b	264.6 ± 6.2 b	459.8 ± 25.5 a	180.3 ± 11.6 a	397.9 ± 2.6 ab
	H	185.3 ± 1.6 a	290.4 ± 14.0 a	221.6 ± 4.0 a	228.1 ± 4.7 a	208.5 ± 0.2 a	250.1 ± 0.2 a	468.4 ± 9.1 a	182.1 ± 5.4 a	362.4 ± 1.6 a
	MEAN	199.3A	317.9AB	250.2AB	233.8E	210.6FG	255.7E	463.2CD	179.8B	371.0CD
MIA	C	225.3 ± 5.0 b	371.9 ± 8.9 c	292.0 ± 2.0 b	223.9 ± 5.6 a	200.0 ± 6.6 a	242.8 ± 2.1 a	450.4 ± 2.0 b	172.9 ± 1.2 a	344.7 ± 1.7 a
	I	223.0 ± 5.7 b	345.0 ± 4.1 b	279.7 ± 6.4 b	240.7 ± 7.0 a	207.0 ± 2.5 a	261.0 ± 5.9 a	438.9 ± 1.9 a	174.3 ± 2.5 a	379.8 ± 2.0 c
	H	202.4 ± 2.0 a	315.6 ± 8.7 a	242.0 ± 2.4 a	222.5 ± 8.9 a	204.3 ± 4.5 a	240.8 ± 15.1 a	458.2 ± 2.7 c	184.8 ± 1.3 a	358.5 ± 2.0 b

Table 2.
 Cont.

CL	T	CHLOROGENIC ACID [mg kg ^{−1} f.m.]			ASCORBIC ACID [mg kg ^{−1} f.m.]			CITRIC ACID [mg kg ^{−1} f.m.]		
		2020	2021	2022	2020	2021	2022	2020	2021	2022
MEAN		216.9BC	344.2ABC	271.2ABC	229.1CDE	203.8DEF	248.2CDE	449.2BCD	177.3B	361.0ABCD
TACJA	C	200.1 ± 5.2 b	333.6 ± 1.6 c	257.7 ± 9.5 b	234.3 ± 3.2 a	206.4 ± 2.9 a	250.6 ± 2.5 a	444.8 ± 4.9 ab	177.1 ± 2.8 a	340.5 ± 3.8 a
	I	202.7 ± 0.4 b	313.6 ± 1.4 b	246.9 ± 9.9 b	245.8 ± 7.2 a	217.3 ± 1.0 b	267.9 ± 0.8 a	429.6 ± 9.8 a	183.5 ± 7.4 a	371.8 ± 8.5 b
	H	176.3 ± 0.9 a	276.2 ± 1.1 a	210.8 ± 1.1 a	231.2 ± 3.3 a	203.6 ± 2.8 a	256.6 ± 10.2 a	459.5 ± 3.9 b	180.3 ± 5.2 a	359.3 ± 3.0 b
MEAN		193.1A	307.8A	238.5A	237.1E	209.1EFG	258.4E	444.7BC	180.3	357.2ABCD
TAJFUN	C	234.3 ± 6.6 b	390.6 ± 11.1 c	303.7 ± 8.6 c	221.0 ± 2.2 a	198.5 ± 2.1 ab	241.0 ± 1.8 a	433.8 ± 2.7 b	170.3 ± 2.2 a	332.0 ± 2.0 a
	I	227.4 ± 1.9 b	346.7 ± 3.0 ab	285.3 ± 4.2 b	238.7 ± 6.9 b	206.1 ± 4.1 b	257.1 ± 3.7 b	421.2 ± 1.4 a	183.2 ± 3.6 b	365.8 ± 1.7 c
	H	216.3 ± 2.2 a	329.5 ± 3.4 a	255.3 ± 6.7 a	234.0 ± 3.7 b	197.0 ± 3.1 a	250.7 ± 3.0 a	439.5 ± 6.8 b	191.9 ± 3.9 c	343.8 ± 5.5 b
MEAN		226.0CD	355.6BCD	281.5BC	231.2DE	200.5CD	249.6E	431.5ABC	181.8B	347.2ABCD
MEAN		214.5	344.8	267.0	223.9	199.4	244.6	442.4	174.9	355.1

a–c indicate no significant differences among cultivation treatments (C—control, N—supplementary irrigation, H—hydrogel) within each cultivar and column; A–G indicate no significant differences among cultivar means within each column (Tukey’s HSD test, $p \leq 0.05$).

The obtained results are also consistent with observations reported by Bienia et al. [39], who showed that weather conditions, particularly soil water deficiency, significantly influenced tuber quality and postharvest stability. Previous studies investigating the effects of climatic factors on the quality of plant-derived products indicate that environmental conditions during plant growth, especially temperature and water availability, determine subsequent postharvest tissue responses [40,41]. High temperatures and water deficits during the growing season affect plant metabolism by accelerating physiological processes and reducing tissue stability, which may increase susceptibility to browning and contribute to other postharvest quality defects [40].

Similar relationships have been demonstrated in studies on internal browning of apples. Weather conditions occurring during the growing season significantly influenced the incidence and severity of browning symptoms [41]. The authors showed that differences in thermal and climatic conditions among growing seasons affected apple susceptibility to internal browning, highlighting the importance of preharvest environmental conditions in maintaining tissue stability.

Although the mechanisms responsible for potato tuber browning and apple internal browning differ, both studies indicate that the course of weather conditions during the growing season plays a crucial role in determining the postharvest quality of plant material. This conclusion is consistent with the results obtained in the present study, in which tubers produced under the wetter and more moderate conditions of 2020 exhibited lower susceptibility to browning than those obtained during the drier and warmer season of 2021.

The highest mean blackspot index values were recorded for the cultivars Bohun (0.449 AU₄₇₅), Baltic Fire (0.418 AU₄₇₅), Tajfun (0.416 AU₄₇₅), and American Rose (0.415 AU₄₇₅) (Figure 2). In contrast, the lowest values were observed for Golden Marie and Ismena, reaching 0.312 and 0.304 AU₄₇₅, respectively (Figure 2). According to the classification of susceptibility to enzymatic browning proposed by Dean et al. [35], American Rose, Bohun, Baltic Fire, and Tajfun were classified as moderately susceptible to browning, whereas Golden Marie and Ismena were classified as moderately resistant cultivars. This relationship was observed in each year of the study, indicating the significant influence of genotype on oxidative processes [9,12,42].

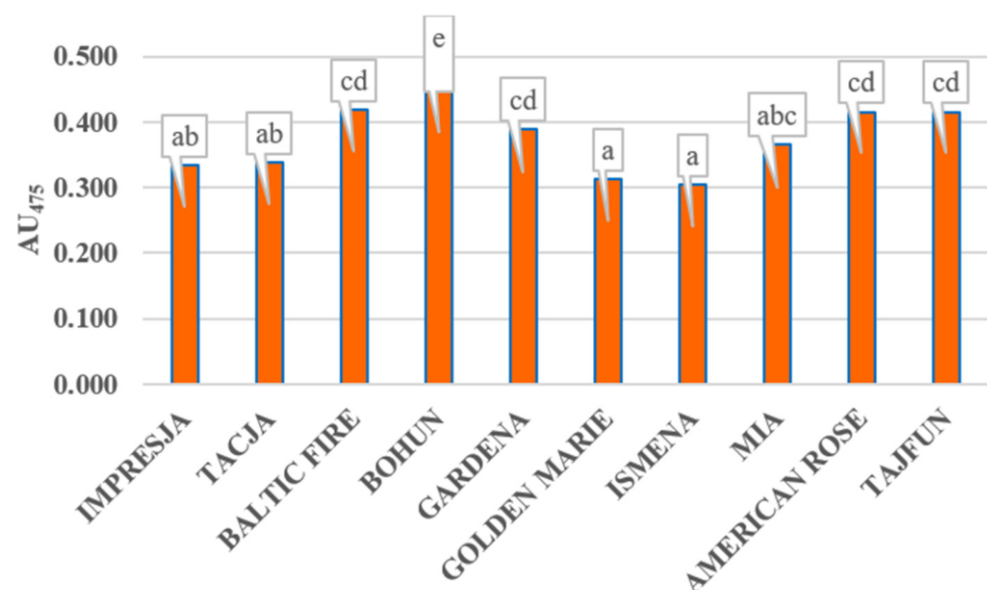


Figure 2. Oxidation potential of potato tubers depending on the cultivar (values represent three-year averages from 2020 to 2022 for freshly harvested tubers). a–e—means sharing the same letter are not significantly different (significance level of 0.05 using Tukey's method).

Differences among cultivars in tuber susceptibility to browning may result from their phenological characteristics, particularly maturity group and degree of tuber maturity at harvest. These genetically determined traits influence physiological processes occurring in tubers and determine their responses to environmental stress factors and postharvest changes. Studies by Meng et al. [43] demonstrated that tuber maturity at harvest significantly affects susceptibility to enzymatic flesh browning. Tubers harvested at later maturity stages exhibited greater susceptibility to browning than those harvested earlier. According to Meng et al. [43], this phenomenon is associated with increased accumulation of free amino acids, including tyrosine.

Similar observations were reported by Wszelaczyńska et al. [12] and Pobereźny et al. [13], who demonstrated that potato cultivars differ in their responses to abiotic stresses and that their metabolism and oxidative potential are modified by genotype. Consequently, cultivars belonging to different maturity groups may exhibit distinct metabolic patterns during tuber maturation. This may influence their susceptibility to postharvest browning, independently of differences in enzymatic activity.

The statistical analysis performed in the present study (ANOVA followed by Tukey's test) revealed significant differences among maturity groups in mean enzymatic browning values (Figure 3). Very early-maturing cultivars (0.246; 0.409; 0.351 AU₄₇₅) and medium early-maturing cultivars (0.291; 0.441; 0.387 AU₄₇₅) exhibited significantly lower susceptibility to browning compared with medium-late cultivars (0.313; 0.502; 0.432 AU₄₇₅) (Figure 3). These results support the hypothesis that cultivar phenology is associated with resistance to postharvest oxidative processes.

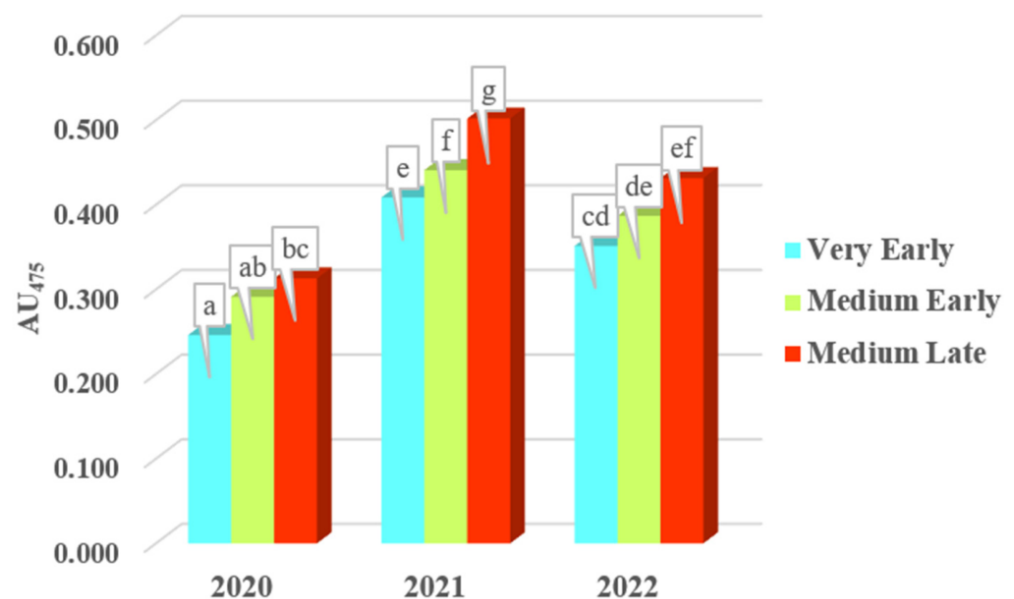


Figure 3. Oxidative potential of potato tubers depending on the earliness group and year of study (freshly harvested tubers). a–g—means sharing the same letter are not significantly different (significance level of 0.05 using Tukey's method).

Among the evaluated cultivars, the lowest susceptibility to browning was observed in very early-maturing cultivars (Impresja and Tacja), followed by medium early-maturing cultivars (Baltic Fire, Bohun, Gardena, Golden Marie, and Mia) and medium-late cultivars (American Rose and Tajfun) (Figures 2 and 3).

Furthermore, a significant effect of the applied agrotechnological practices on the susceptibility of tubers of the analyzed cultivars to browning was observed. The application of hydrogel (H) resulted in lower oxidative potential values compared with treatments where supplemental irrigation (I) was applied (Figure 4a–c). This relationship was observed

in each year of the study; however, the protective effect of hydrogel was particularly pronounced in 2022, when the blackspot index decreased from 0.425 to 0.334 AU₄₇₅. This year was characterized by water deficiency during the spring period, followed by favorable meteorological conditions during summer (Figure 1). A similar, although less pronounced, effect was observed in 2021, with a reduction from 0.475 to 0.423 AU₄₇₅ (Figure 4a–c).

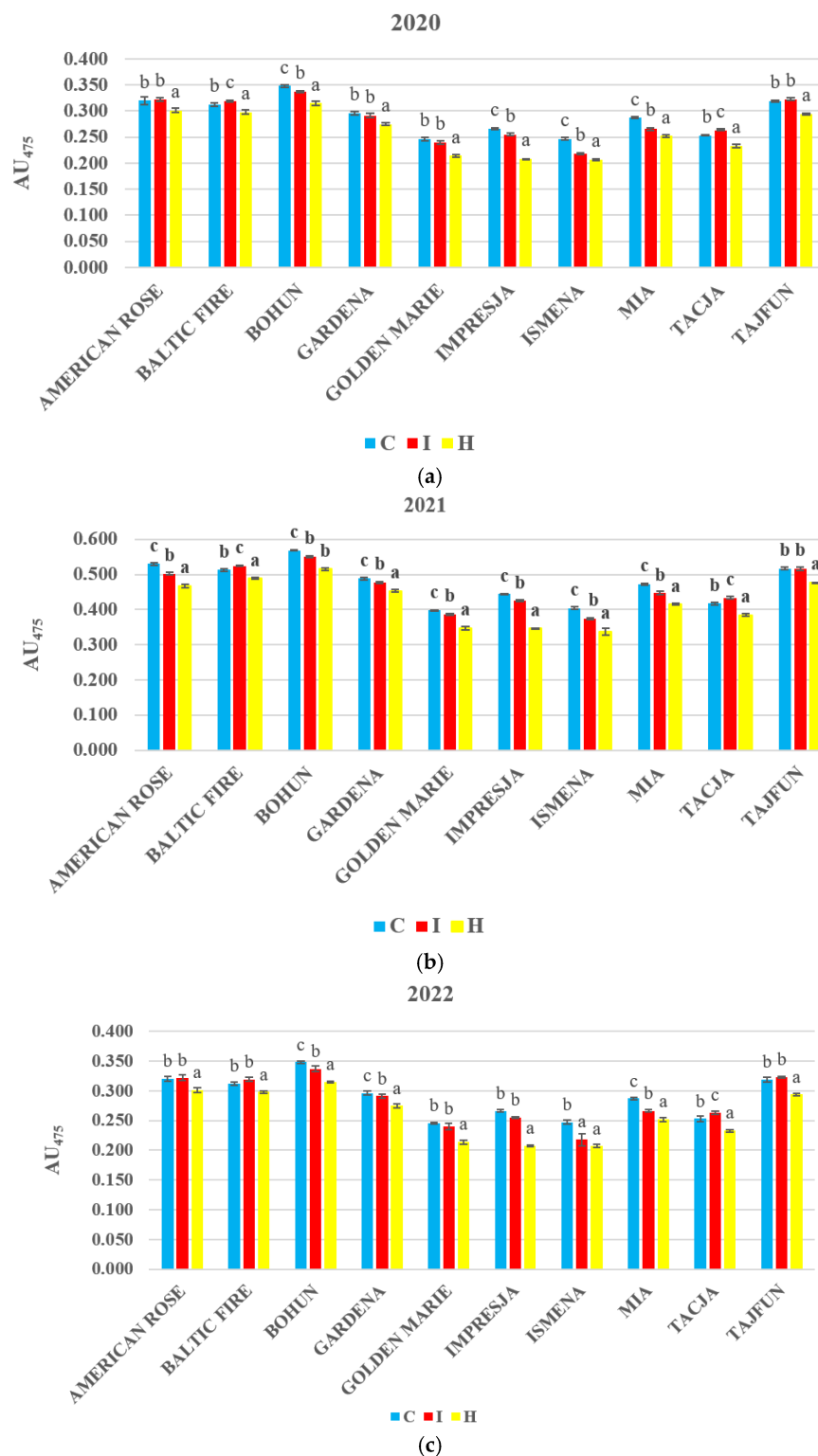


Figure 4. Oxidative potential of potato tubers depending on the cultivar and year of study ((a) 2020, (b) 2021, (c) 2022). C—control, N—supplementary irrigation, H—hydrogel. a–c—means sharing the same letter are not significantly different (significance level of 0.05 using Tukey’s method).

Limited water availability during spring may have increased the susceptibility of tubers to oxidative processes and enzymatic browning. By improving water retention in the root zone, hydrogel may have contributed to maintaining plant water status and mitigating the effects of water deficit, which could subsequently have favored more stable physiological conditions and lower susceptibility of tubers to enzymatic browning. However, plant water status and oxidative stress were not directly measured in the present study; therefore, these mechanisms should be considered as possible explanations for the observed reduction in oxidative potential rather than as directly demonstrated effects of hydrogel application. Favorable summer conditions may have alleviated the effects of early-season growth limitations, potentially supporting more favorable physiological conditions during tuber development and contributing to the lower susceptibility to enzymatic browning observed in the present study. Supplemental irrigation reduced browning susceptibility to a lesser extent than hydrogel application, which may have resulted from lower stability of water availability over time.

In the study by Wszelaczyńska et al. [12], irrigation applied during the growing season to different potato cultivars reduced oxidative potential immediately after harvest. The decrease in the browning index averaged 6.7% compared with non-irrigated tubers. In the present study, hydrogel application reduced oxidative potential by an average of 14.5%, whereas supplemental irrigation resulted in a reduction of 2.6% (mean values across years). The reduction in oxidative potential following hydrogel application amounted to 10.6%, 11.2%, and 21.8% in 2020, 2021, and 2022, respectively (Figure 4a–c). In the case of supplemental irrigation, the reduction was considerably lower and reached 2.2%, 2.4%, and 3.2%, respectively (Figure 4a–c).

Among the evaluated cultivars, the greatest reduction in oxidative potential after hydrogel application was observed in Impresja and Ismena, whereas under supplemental irrigation the strongest response was recorded for Ismena and Mia (Figure 4a–c). In the case of Baltic Fire, the influence of the applied agrotechnological treatments was the least pronounced (Figure 4a–c).

Furthermore, the oxidative potential of tubers was significantly affected by interactions among the studied factors, particularly year $\times$ cultivar and year $\times$ treatment (Table 1). This indicates that the response of genotypes to the applied technologies varied depending on meteorological conditions occurring during a given growing season. The significant year $\times$ cultivar interaction demonstrates differences in the stability of oxidative potential among the evaluated genotypes under changing environmental conditions. This may reflect cultivar-specific differences in the response of tubers to environmental conditions, including water availability, although the physiological and biochemical mechanisms underlying these differences were not directly assessed in the present study. In practical terms, these differences indicate a varying ability of cultivars to maintain tuber quality under fluctuating environmental conditions.

Due to the significant year $\times$ treatment interaction, the effects of hydrogel application and supplemental irrigation were analyzed separately for each year. In 2021, which was characterized by pronounced water deficit, the effects of hydrogel and irrigation were more evident than in the other growing seasons, whereas in years with more favorable water conditions, differences between treatments were less pronounced (Figure 4a–c). This indicates that the effectiveness of the applied technologies was strongly dependent on weather conditions, and their beneficial effects were particularly visible under water-limited conditions.

Similar conclusions were reported by Pobereźny et al. [13], who demonstrated that potato tuber oxidative potential is influenced not only by individual experimental factors (cultivar, mineral fertilization, and application of biostimulants), but also by interactions

among these factors. The authors showed that cultivars differed in their responses to the applied treatments, indicating the combined influence of genetic and environmental factors in regulating oxidative processes.

The obtained results are also consistent with findings reported by other authors, including Wszelaczyńska et al. [12], Djaman et al. [44], and Camargo et al. [45], who indicated that the effectiveness of irrigation and water management strategies in potato cultivation is strongly modified by meteorological conditions and the intensity of water stress occurring during a particular growing season.

3.2. Chlorogenic Acid

Chlorogenic acid is the predominant phenolic compound in potato tubers, usually accounting for 70–90% of the total phenolic acids present in potato tissues [46]. Its content varies widely, ranging from 148 to 900 mg kg^{−1} fresh weight, while pigmented-flesh cultivars may contain considerably higher levels, reaching up to 4000 mg kg^{−1} fresh weight [47,48]. In the present study, the mean chlorogenic acid content was 287.7 mg kg^{−1} fresh weight. The lowest value was recorded in 2020 for the cultivar Tacja (176.3 mg kg^{−1} fresh weight), whereas the highest concentration was observed in Bohun in 2021 (414.8 mg kg^{−1} fresh weight) (Table 2). The mean chlorogenic acid content was 214.5 mg kg^{−1} fresh weight in 2020 and 344.8 mg kg^{−1} fresh weight in 2021 (Table 2). These results indicate substantial variation among cultivars and demonstrate the significant influence of environmental conditions during individual growing seasons. They also confirm the importance of both genetic and agrotechnological factors in shaping the phenolic profile of potato tubers (Table 1).

From a plant physiological perspective, chlorogenic acid functions not only as a defense-related compound involved in plant responses to abiotic stress but also contributes to limiting susceptibility to pathogen infection. Additionally, it participates in free radical scavenging and metal ion chelation, thereby enhancing the antioxidant potential of potato tissues [7,8]. Moreover, chlorogenic acid is considered a key determinant of potato tuber oxidative potential, as it influences the intensity of enzymatic browning. High concentrations of this compound increase the availability of substrates for polyphenol oxidase (PPO), directly contributing to enhanced oxidative potential and more intensive discoloration processes [7,10,12,13].

This relationship was confirmed in the present study, as the year 2021, characterized by the highest chlorogenic acid concentrations, also exhibited the greatest susceptibility to enzymatic browning. This was supported by the positive correlation between chlorogenic acid content and oxidative potential, with correlation coefficients of $r = 0.810$, $r = 0.757$, and $r = 0.852$ ($p < 0.05$) for 2020, 2021, and 2022, respectively (Figure 5). Therefore, the reduction in browning after mechanical damage and during potato processing is associated with the content of phenolic compounds, including chlorogenic acid, as well as PPO activity [7,8].

The application of hydrogel was shown to significantly reduce chlorogenic acid content in potato tubers (Table 2). This effect was particularly evident in 2021 and 2022, when low precipitation levels were recorded. The reduction in chlorogenic acid content amounted to 14.2% and 16.1%, respectively. The cultivars that showed the strongest response to hydrogel application were Ismena and Golden Marie (Table 2). These results suggest that the lower chlorogenic acid content observed following hydrogel application may be associated with alleviation of water stress and a potentially lower requirement for activation of defense-related pathways involved in chlorogenic acid biosynthesis.

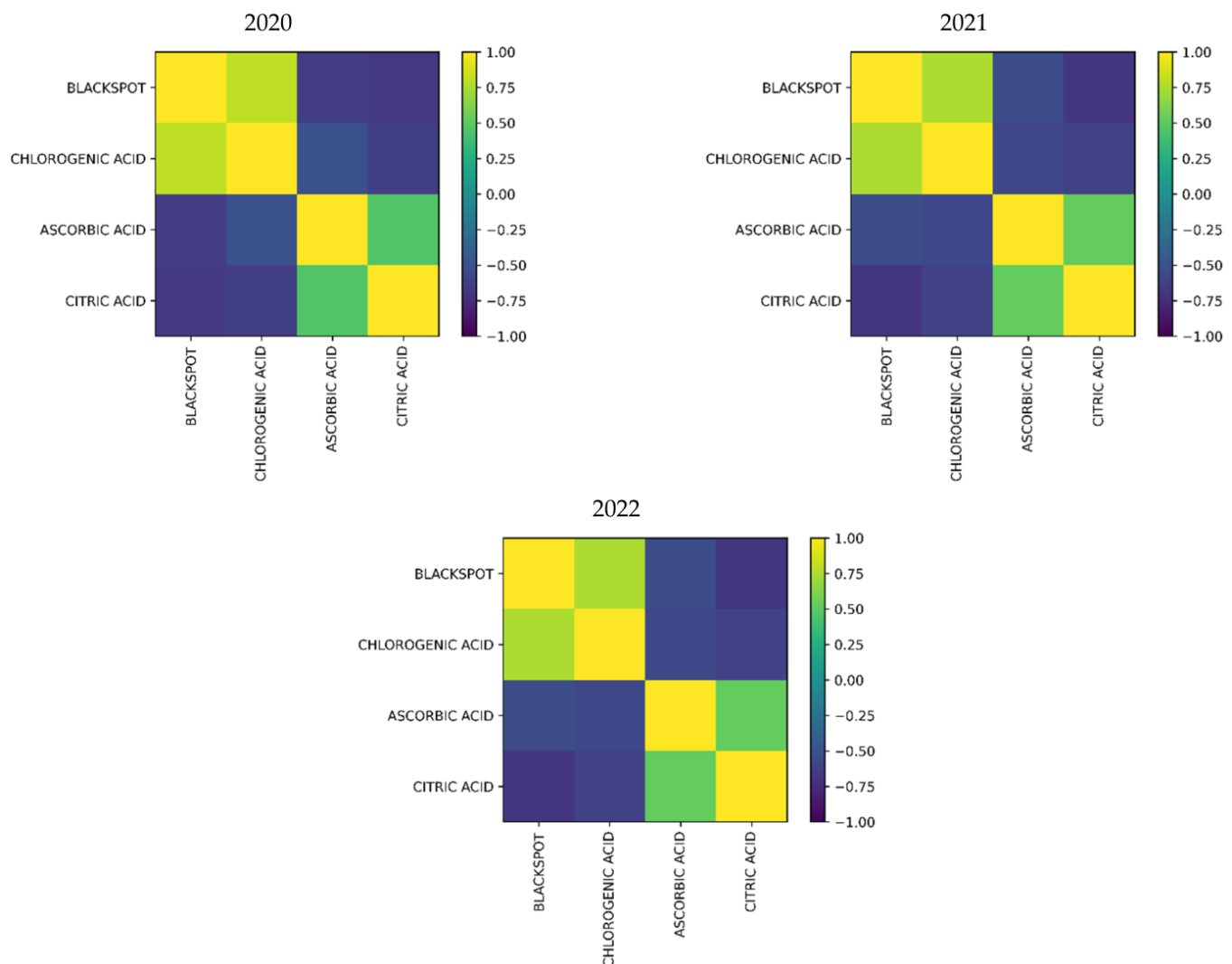


Figure 5. Spearman's rank correlation matrix between blackspot formation and selected chemical compounds in tubers in 2020–2022.

Hydrogel, due to its high water-absorption capacity and gradual water release properties, acts as a soil moisture regulator, reducing fluctuations in water availability within the root zone. The improved water-retention capacity of the soil following hydrogel application may have alleviated the effects of water deficit and, consequently, may have limited the activation of defense-related pathways associated with phenolic compound production. Under water-deficit conditions, increased levels of reactive oxygen species (ROS) and enhanced activity of enzymes such as phenylalanine ammonia-lyase (PAL) have been reported to promote the synthesis of phenolic compounds, including chlorogenic acid [49–51]. Therefore, the lower chlorogenic acid content observed following hydrogel application may be related to alleviation of water-deficit conditions and potentially lower activation of defense-related pathways involved in phenolic biosynthesis [52–54]. However, PAL activity, ROS levels, and other components of the phenylpropanoid pathway were not directly assessed in the present study, and this mechanism should therefore be regarded as a possible explanation rather than a demonstrated causal relationship.

3.3. Ascorbic and Citric Acids

Ascorbic and citric acids exhibited an opposite relationship with oxidative potential compared with chlorogenic acid in each year of the study. The highest ascorbic acid content was recorded in 2022, reaching 244.8 mg kg⁻¹ fresh weight, whereas the lowest

concentration was observed in 2021 (199.4 mg kg⁻¹ fresh weight) (Table 2). The conditions prevailing in 2022, characterized by favorable thermal and moisture conditions, may have promoted intensive plant metabolic activity and enhanced vitamin C biosynthesis (Figure 1). In contrast, citric acid content was highest in 2020, with an average value of 442.4 mg kg⁻¹ fresh weight and lowest in 2021 (174.9 mg kg⁻¹ fresh weight) (Table 2). High precipitation levels in 2020 may have supported metabolic activity and organic acid accumulation in tubers, whereas limited water availability in 2021 may have disturbed energy metabolism and reduced accumulation of this compound.

Unlike chlorogenic acid, supplemental irrigation most frequently increased ascorbic acid content, while hydrogel application contributed to maintaining its concentration at a stable level or resulted in a slight increase (Table 2). Hydrogel application also supported the maintenance of higher citric acid levels under stress conditions, which may indicate improved stabilization of cellular metabolism. These findings suggest that improved plant water availability may enhance the activity of antioxidant systems and promote the biosynthesis of reducing compounds [31].

The contents of both ascorbic and citric acids were primarily influenced by environmental conditions occurring in individual growing seasons ($p < 0.001$). The effect of year was stronger than that of cultivar, indicating that seasonal conditions played a dominant role in determining the accumulation of these compounds in potato tubers. Significant year $\times$ cultivar and year $\times$ treatment interactions confirmed that cultivar responses to the applied technologies were dependent on environmental conditions (Table 1).

The obtained results are consistent with previous studies demonstrating that ascorbic and citric acid contents in potato tubers are regulated by multiple factors during cultivation, including temperature, water availability, weather conditions, and applied agrotechnological practices [55,56]. Therefore, variation in environmental conditions among growing seasons influenced not only the concentration of these compounds but also the differential responses of cultivars to water management strategies, including hydrogel application and supplemental irrigation [12].

3.4. Storage

Table 3 presents the percentage changes in oxidation potential and the content of organic acids in potato tubers after six months of storage. The results revealed significant differences in both the magnitude and direction of changes among cultivars, cultivation treatments, and study years. After six months of storage, the susceptibility of tubers to enzymatic flesh browning increased by an average of 12.6%. Comparable findings were reported by Wszelaczyńska et al. [12], who observed an average 15.9% increase in the oxidation potential of potato tubers following storage. In contrast, Pobereżny et al. [42] reported a substantially greater increase in browning susceptibility after six months of storage, averaging 28.7% across all cultivars.

Many authors have indicated that differences in tuber susceptibility to browning observed immediately after harvest and following storage may result from the fact that water conditions during the growing season shape the initial physiological and biochemical status of tubers, whereas further dynamic metabolic changes occur during storage. It has been demonstrated that water management practices and conditions during the growing season can affect tuber quality, and that these effects may subsequently be modified during storage [12]. Particularly important is the fact that during long-term potato storage, the contents of sugars, chlorogenic acid, and ascorbic acid change, which may lead to changes in the oxidative potential of tubers and their susceptibility to enzymatic browning [12,13]. Furthermore, irrigation practices and the maturity status of tubers at harvest have been shown to affect the dynamics of quality changes occurring during subsequent storage [12,13,43].

It may therefore be hypothesized that the differential effects of supplemental irrigation and hydrogel application on water conditions during the growing season may have resulted in differences in the physiological status of tubers, the consequences of which became manifest in different ways during storage. This interpretation should, however, remain cautious, as not all biochemical parameters that could explain changes in susceptibility to browning during storage were directly measured in the present study.

Table 3. Percentage changes in blackspot and content of organic acids of ten cultivars after storage. (C—control; I—supplemental irrigation; H—hydrogel).

CULTIVAR	TREATMENT	BLACKSPOT			CHLOROGENIC ACID			ASCORBIC ACID			CITRIC ACID		
		2020	2021	2022	2020	2021	2022	2020	2021	2022	2020	2021	2022
AMERICAN ROSE	C	12.6	11.6	13.1	5.6	8.5	8.2	−6.8	−7.7	−7.8	3.0	3.1	4.3
AMERICAN ROSE	I	12.7	11.7	13.3	5.9	7.2	6.5	−5.8	−7.6	−7.8	3.1	3.4	4.9
AMERICAN ROSE	H	13.4	12.0	13.1	5.2	7.1	6.3	−6.7	−8.2	−8.8	2.3	3.9	5.3
Mean		12.9	11.8	13.2	5.6	7.6	7.0	−6.4	−7.8	−8.1	2.8	3.5	4.8
BALTIC FIRE	C	13.7	11.4	13.1	6.0	8.0	7.8	−6.1	−7.4	−10.0	2.6	3.5	4.7
BALTIC FIRE	I	13.2	11.9	13.4	5.7	8.0	7.3	−6.3	−7.3	−8.4	2.4	3.4	5.3
BALTIC FIRE	H	13.2	12.1	12.4	5.9	7.1	6.5	−5.2	−7.0	−9.3	2.4	3.4	5.1
Mean		13.3	11.8	13.0	5.9	7.7	7.2	−5.9	−7.2	−9.2	2.5	3.4	5.0
BOHUN	C	12.3	13.0	13.8	6.1	6.7	7.4	−6.7	−7.7	−9.9	2.4	3.1	4.1
BOHUN	I	12.6	12.9	13.4	5.8	6.4	7.1	−6.7	−7.9	−9.1	2.4	3.2	4.2
BOHUN	H	12.6	12.9	13.1	6.1	6.0	6.8	−6.3	−9.0	−9.6	2.8	3.2	4.1
Mean		12.5	12.9	13.4	6.0	6.3	7.1	−6.6	−8.2	−9.5	2.5	3.1	4.1
GARDENA	C	12.4	11.9	14.0	5.7	6.6	7.6	−6.7	−8.4	−7.2	2.6	3.1	4.5
GARDENA	I	11.9	12.0	14.0	6.7	6.3	6.8	−6.9	−8.8	−7.7	2.7	3.2	5.1
GARDENA	H	11.5	12.0	13.8	6.6	5.9	6.6	−5.3	−8.8	−8.3	3.0	3.0	4.4
Mean		11.9	12.0	13.9	6.3	6.3	7.0	−6.3	−8.7	−7.7	2.7	3.1	4.7
GOLDEN MARIE	C	12.1	12.1	13.5	6.2	7.1	8.1	−6.6	−8.3	−7.2	2.5	3.8	3.9
GOLDEN MARIE	I	11.7	12.1	13.7	6.1	7.2	8.4	−6.8	−8.3	−7.7	2.3	3.2	5.4
GOLDEN MARIE	H	11.7	12.0	13.3	6.7	8.1	6.4	−6.6	−8.5	−8.1	2.8	3.2	4.1
Mean		11.8	12.0	13.5	6.4	7.5	7.6	−6.7	−8.3	−7.7	2.5	3.4	4.4
IMPRESJA	C	12.9	11.0	13.9	6.9	7.1	9.5	−6.8	−8.1	−8.3	2.6	4.1	4.2
IMPRESJA	I	13.0	11.1	13.6	6.2	7.0	9.1	−7.3	−8.3	−8.4	2.4	4.0	4.0
IMPRESJA	H	11.9	11.1	13.8	6.1	7.3	7.3	−7.4	−9.0	−8.7	2.3	3.9	4.8
Mean		12.6	11.1	13.7	6.4	7.1	8.6	−7.2	−8.5	−8.5	2.4	4.0	4.3
ISMENA	C	12.4	12.0	13.8	6.1	7.0	10.0	−6.2	−8.0	−8.4	2.9	3.5	4.2
ISMENA	I	12.1	12.0	13.9	5.5	7.0	9.9	−5.1	−8.5	−8.5	3.0	3.1	5.1
ISMENA	H	12.7	11.9	13.9	6.3	7.0	9.5	−6.6	−7.9	−8.8	2.9	3.2	4.1
Mean		12.4	12.0	13.9	5.9	7.0	9.8	−6.0	−8.1	−8.6	2.9	3.3	4.5
MIA	C	12.3	11.4	13.7	7.2	7.0	8.0	−6.6	−8.6	−7.8	2.7	3.4	4.2
MIA	I	12.4	11.1	13.6	7.0	6.5	8.2	−7.4	−8.6	−7.7	2.5	3.4	4.2
MIA	H	13.1	10.8	13.0	7.2	6.6	7.9	−7.6	−8.9	−7.6	2.7	3.3	4.5
Mean		12.6	11.1	13.4	7.1	6.7	8.0	−7.2	−8.7	−7.7	2.6	3.4	4.3
TACJA	C	13.1	11.7	13.7	7.0	6.6	9.5	−7.6	−8.5	−7.8	2.8	3.6	4.5
TACJA	I	12.8	11.8	13.9	6.9	6.9	8.8	−7.4	−8.0	−8.2	2.6	3.5	4.5
TACJA	H	12.7	11.9	13.9	7.0	6.8	8.1	−7.3	−8.3	−8.7	2.7	3.3	4.1
Mean		12.9	11.8	13.8	7.0	6.7	8.8	−7.4	−8.3	−8.2	2.7	3.4	4.3
TAJFUN	C	13.3	11.6	13.6	6.8	7.6	7.6	−7.0	−8.9	−8.3	3.0	3.7	4.1
TAJFUN	I	14.0	12.0	13.6	7.0	7.6	7.3	−6.4	−9.1	−7.2	3.1	3.3	4.4
TAJFUN	H	12.9	12.0	13.5	7.3	7.9	6.8	−6.3	−8.9	−6.7	3.0	3.1	4.2
Mean		13.4	11.9	13.6	7.0	7.7	7.2	−6.6	−9.0	−7.4	3.0	3.4	4.3
Mean across cultivars		12.6	11.8	13.5	6.4	7.1	7.8	−6.6	−8.3	−8.3	2.7	3.4	4.5
Mean across C		12.7	11.8	13.6	6.4	7.2	8.4	−6.7	−8.2	−8.3	2.7	3.5	4.3
Mean across I		12.6	11.9	13.6	6.3	7.0	7.9	−6.6	−8.2	−8.1	2.6	3.4	4.7
Mean across H		12.6	11.9	13.4	6.4	7.0	7.2	−6.5	−8.5	−8.5	2.7	3.4	4.5
Mean across years			12.7			7.1			−7.7			3.5	

Other authors have emphasized that the increased susceptibility of potato tubers to enzymatic browning after long-term storage is strongly influenced by storage conditions, particularly storage duration and temperature [42,57,58].

However, according to Pobereźny et al. [13], the enhanced susceptibility to enzymatic browning following storage may result from low storage temperatures (4 °C), which promote loss of cell turgor and increase the susceptibility of tuber tissues to mechanical damage. Such damage facilitates contact between polyphenol oxidase and its phenolic substrates, thereby accelerating enzymatic oxidation reactions and intensifying flesh browning.

The present study also demonstrated considerable year-to-year variation in the susceptibility of potato tubers to enzymatic browning after storage. The greatest changes were recorded in 2022, whereas the smallest were observed in 2021 (Table 3). In 2020, changes in oxidation potential ranged from 11.5% to 14.0%, indicating a moderate increase in tuber susceptibility to flesh browning during storage. The largest increases were observed in the cultivars Baltic Fire and Tajfun, while the smallest changes were recorded for Golden Marie and Gardena.

In 2021, the increase in oxidation potential ranged from 10.8% to 13.0%, indicating a relatively lower increase in susceptibility to enzymatic browning after storage. The greatest changes were observed in the cultivar Bohun, whereas Mia and Impresja exhibited the lowest increases.

In 2022, the changes ranged from 12.4% to 14.0%, representing the highest overall increase among the three study years. The greatest increases in oxidation potential were recorded for the cultivars Gardena, Ismena, and Tacja.

The significant effect of cultivar on changes in oxidation potential following long-term storage has also been reported by Pobereźny et al. [13], Wszelaczyńska et al. [12], Pobereźny et al. [42], and Keutgen et al. [59], confirming that the response of potato tubers to storage is strongly genotype-dependent. Differences in blackspot susceptibility among maturity groups were relatively small and less pronounced than those observed among individual cultivars or growing seasons. However, maturity class was associated with certain differences in biochemical composition. Very early cultivars tended to exhibit higher chlorogenic acid contents, whereas medium-late cultivars generally maintained higher ascorbic and citric acid contents after storage. These findings suggest that maturity class had a greater influence on the accumulation of organic acids than on the susceptibility of tubers to enzymatic browning.

In the present study, supplemental irrigation resulted in a slight increase in the susceptibility of potato tubers to enzymatic browning after storage compared with the control treatment. This effect was most evident in the cultivars American Rose and Tajfun (Table 3). In contrast, hydrogel application frequently stabilized the oxidation potential or slightly reduced its increase after storage. This may indicate that improved soil water availability alleviated environmental stress during plant growth, thereby enhancing the physiological stability of tuber tissues and reducing their susceptibility to internal damage during storage [13,60]. Similar relationships were reported by Wszelaczyńska et al. [12], who emphasized that reducing abiotic stress during plant development may decrease the oxidation potential of potato tubers after harvest and reduce their susceptibility to enzymatic browning. Furthermore, Pobereźny et al. [13] suggested that environmental stresses occurring during the growing season, together with physiological processes taking place during storage [61], may substantially affect the storage stability of potato tubers and the intensity of oxidative reactions in their tissues. These processes promote the oxidation of phenolic compounds and the formation of enzymatic browning products. Takahama [62] demonstrated that oxidative enzymes, particularly peroxidases, catalyze the oxidation of phenolic compounds in plant tissues, thereby accelerating the browning process.

The intensification of enzymatic browning is also associated with changes in the chemical composition of potato tubers occurring during storage [63]. In the present study, long-term storage significantly affected the concentrations of the analyzed organic acids (Table 3). After six months of storage, chlorogenic acid and citric acid contents increased by an average of 7.1% and 3.4%, respectively. Comparable results were reported by Pobereżny et al. [13] and Wszelaczyńska et al. [12], who observed increases in chlorogenic acid content of 7.3% and 5.5%, respectively, and increases in citric acid content of 11.1% and 2.5% after six months of storage. The increase in chlorogenic acid and other organic acids during storage may be associated with ongoing metabolic transformations in tuber tissues and with plant responses to storage-induced stress. As emphasized by Wszelaczyńska et al. [12], phenolic compounds, including chlorogenic acid, play an important role in the plant defense system, and their biosynthesis may be enhanced under abiotic stress conditions. The considerable increase in chlorogenic acid content observed in the present study could potentially also be related to progressive water loss from the tubers, which may have resulted in a concentration effect of metabolites within the tissues. However, this explanation remains hypothetical because tuber mass loss and changes in dry matter content during storage were not directly measured in the present study. This consideration is particularly relevant because metabolite concentrations were expressed on a fresh-weight basis. Likewise, the increase in organic acid content may reflect changes in the activity of enzymes involved in the tricarboxylic acid (TCA) cycle. Previous studies have shown that low-temperature storage may promote the accumulation of citrate and other TCA cycle intermediates as part of the regulation of respiratory metabolism and the adaptive response of tuber tissues to storage-related stress [64–66].

The magnitude of changes in chlorogenic and citric acid contents also varied considerably among study years. In 2020, chlorogenic acid content increased by 5.2–7.3%, whereas in 2021 the increases generally exceeded 7.0%. The greatest increases were recorded for the cultivars American Rose, Baltic Fire, and Tajfun. The largest changes, however, were observed in 2022, when chlorogenic acid content increased by 8.0–10.0% in the cultivars Ismena and Impresja.

A contrasting trend was observed for ascorbic acid, the concentration of which consistently declined during storage, with an average decrease of 7.7% after six months (Table 3). In 2020, losses ranged from 5.1% to 7.6%, whereas in 2021 they were greater and in many cases exceeded 8.0%. A similarly high level of degradation was maintained in 2022, when the decrease reached as much as 9.5% in some cultivars. The greatest losses were recorded in the cultivars Bohun and Impresja. The decline in vitamin C content during storage is a well-documented phenomenon and is primarily attributed to oxidative processes occurring in plant tissues. Ascorbic acid is one of the principal cellular antioxidants and is progressively depleted while scavenging reactive oxygen species generated during normal metabolism and under storage-induced stress conditions [13]. The depletion of ascorbic acid reduces the antioxidant capacity of tuber tissues and may consequently enhance the oxidation of phenolic compounds, thereby increasing susceptibility to enzymatic browning during prolonged storage.

3.5. Limitations and Future Research Perspectives

The results of this study should be interpreted within the context of the experimental conditions. The results of this study provide a basis for further research on the role of supplemental irrigation and hydrogel application in potato production, particularly in relation to the susceptibility of tubers to enzymatic browning after harvest and storage. The differences in precipitation and temperature observed across the three growing seasons highlight the need to investigate these relationships under a wider range of environmental

conditions. Future studies should therefore include multi-year and multi-location field experiments to determine whether the observed responses are consistent across different soil types, climatic conditions, and potato cultivars.

Further research should also focus on optimizing irrigation strategies and hydrogel application rates. Evaluating different irrigation thresholds, water application levels, and hydrogel doses could help identify management practices that improve water-use efficiency while maintaining tuber quality. Particular attention should be given to potential interactions between cultivar characteristics, water availability, and hydrogel application, as these factors may jointly influence the post-harvest quality of potato tubers.

Another important direction is to investigate the mechanisms underlying changes in enzymatic browning susceptibility. Future experiments could examine relationships between blackspot development, concentrations of selected phenolic compounds and organic acids, and the activity of enzymes involved in browning. Extending storage trials to different temperatures and durations would also help determine whether the effects of irrigation and hydrogel application persist under alternative storage conditions. Ultimately, integrating agronomic, biochemical, and post-harvest assessments may support the development of cultivation practices that improve water management while maintaining potato tuber quality during storage.

4. Conclusions

The conducted studies demonstrated that the year of the experiment, reflecting the course of weather conditions during the growing season, was the factor that most strongly determined the analyzed quality parameters of potato tubers.

It was found that both the course of weather conditions during the growing season and the applied cultivation technologies significantly influenced the qualitative stability of potato tubers and their susceptibility to changes occurring during storage. Over the three-year study period, a clear impact of meteorological conditions on the intensity of oxidative processes occurring in tuber tissues was demonstrated. Seasons characterized by higher precipitation levels and more moderate temperatures promoted a lower increase in tuber susceptibility to enzymatic browning, whereas dry and warmer years increased the risk of visual defects associated with flesh browning. This phenomenon is of significant importance from the perspective of commercial quality and storage suitability of tubers.

The application of supplemental irrigation and hydrogel reduced the susceptibility of tuber flesh to enzymatic browning in the studied cultivars. The analysis of interactions further indicated that the effectiveness of the applied technologies mitigating abiotic stress was strongly dependent on weather conditions in a given growing season. The greatest effectiveness of hydrogel application was observed in the year characterized by the highest water deficit during the growing season, suggesting that the beneficial effect of hydrogel was particularly pronounced under water-deficit conditions. In years with higher precipitation totals, the effect of hydrogel was considerably less pronounced. These results suggest that hydrogel application may be particularly relevant for potato production under conditions of limited water availability, although the underlying changes in soil water retention were not directly measured in the present study.

The susceptibility of tubers to enzymatic browning was determined to the greatest extent by the content of chlorogenic acid. An increase in chlorogenic acid content promoted higher values of the oxidative potential of tubers. In contrast, ascorbic acid reduced the intensity of browning due to its antioxidant properties.

At the same time, it was confirmed that the qualitative stability of tubers during storage is shaped by a complex interaction between cultivar-specific characteristics, environmental conditions, and applied agrotechnical practices.

The application of supplemental irrigation and hydrogel in many cases reduced the negative effects of water stress, contributing to lower susceptibility of tubers to browning after long-term storage. However, the responses to the two technologies were not fully consistent. Hydrogel application generally resulted in a more consistent response during storage, whereas supplemental irrigation in some cases was associated with a slight increase in tuber susceptibility to browning after storage. Moreover, the applied technologies contributed to greater stability in changes in the content of the analyzed organic acids during storage. These results indicate that hydrogel and supplemental irrigation may influence tuber quality during storage in different ways depending on the environmental conditions during the growing season. The potential role of improved soil water availability in these responses should be interpreted cautiously, as changes in soil water retention were not directly measured in the present study.

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