PAPER

BIOACTIVE COMPOUNDS IN YELLOW, LIGHT YELLOW, AND CREAM-COLOURED POTATO TUBERS AFTER SHORT-TERM STORAGE AND BOILING

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ABSTRACT

This study measured the changes in bioactive compounds [L-ascorbic acid (AA) and total phenolic (TP) compounds] and antioxidant activity (measured in Trolox equivalents, TE) in six potato (*Solanum tuberosum* L.) varieties with yellow, light-yellow, and cream-coloured flesh after several different treatments. The experimental materials included raw tubers and both peeled and unpeeled tubers that had been boiled. Analyses were conducted immediately after harvest and after 3 months of storage at 5°C and 8°C. Flesh colour significantly affected the AA and TP contents in tubers. The difference in AA content was 0.195 $mg \cdot g^{-1}$ DM between cream- and yellow-coloured tubers and 0.086 $mg \cdot g^{-1}$ DM between cream and light-yellow tubers. Differences in TP contents between tubers with different flesh colours did not exceed 33%. Significant losses in AA were detected in yellow- and light-yellow-fleshed tubers that had been peeled and cooked after harvest (44 and 46%, respectively). Cooking peeled tubers significantly decreased the antioxidant activity in potatoes regardless of flesh colour and storage treatment. Unpeeled cooked tubers had significantly higher antioxidant activity than raw tubers after harvest. Irrespective of flesh colour, high linear correlations were found between (AA)×(TE) for cooked peeled tubers. A significant determination coefficient (R^2) was observed between (TPs)×(TE) for raw and cooked unpeeled light-yellow and yellow-coloured tubers. The linear relationship between TPs and TE after cooking was significant for unpeeled tubers. The greatest matching of the model characteristics of the interdependence of features (ϕ^2) was 75% for (AA) × (TE) and 80% for (TPs) × (TE).

Keywords: antioxidant activity, ascorbic acid, phenolics, boiling, potato, storage

1. INTRODUCTION

Potatoes (*Solanum tuberosum* L.) are a rich source of nutrients, particularly complex carbohydrates (starch), phenolic compounds (HEJTMÀNKOVA *et al*., 2009, LACHMAN *et al*., 2012, NAVARRE *et al*., 2010, RUMBOA *et al*., 2009, TEOW *et al*., 2007), and vitamin C (L-ascorbic acid, AA), with AA levels ranging from 14 to 25 $mg \cdot 100^{-1}$ g fresh matter (FM) depending on the variety (BURGOS *et al*., 2009, GRUDZIŃSKA and ZGÓRSKA, 2011, HAN *et al*., 2004, VALCARCEL *et al*., 2015). The importance of these compounds in the human diet has been emphasized by recent studies on their health-promoting properties (WELCH *et al*., 2005, CAHILL *et al*., 2009). Until recently, it was thought that the processing of potatoes, such as cooking, degrades antioxidants and reduces their activity. However, the impact of processing on antioxidant activity is not always straightforward. For example, RUMBOA et al. (2009) found that a reduction in the natural antioxidant content in a food product (potato extracts) may be accompanied by an increase in antioxidant activity.

Research on the bioactive compounds in potato (LACHMAN and HAMOUZ, 2005, REYES *et al*., 2005, LACHMAN *et al*., 2012, HEJTMÀNKOVA *et al*., 2009, BELLUMORI *et al*., 2017) has focused on variations in potatoes with different flesh colours (e.g., white, red, pink, and purple), growing locations (JANSEN and FLAMME, 2008, LACHMAN *et al*., 2008, VALCARCEL *et al*., 2015, PERLA *et al*., 2012, SILVEIRA *et al*., 2016), and cultivation systems (BRAZINSKIENE *et al*., 2014, GRUDZIŃSKA *et al*., 2016) and the effects of cooking (MULINACCI *et al*., 2008, LACHMAN *et al*., 2012, BURGOS *et al*., 2013, BELLUMORI *et al*., 2017) and blanching conditions (MARANGONI *et al*., 2019). However, these studies have not unequivocally demonstrated a correlation between changes in the levels of bioactive compounds and antioxidant activity in potato tubers after storage or non-peeled tubers after cooking using a best-fit model. In particular, such studies have not been performed in potato varieties with cream, light yellow, and yellow flesh, the most popular flesh colours in Europe.

The aim of this study was to determine the changes in bioactive compound levels and antioxidant activity in raw potatoes and in peeled and unpeeled boiled potato tubers with yellow, light-yellow, and cream-coloured flesh after short-term storage at 5°C and 8°C. We also developed a model describing the association of these changes.

2. MATERIALS AND METHODS

2.1. Chemicals

All reagents used in this study, including 2,6-dichloroindophenol (puriss p.a 97.0%), oxalic acid (puriss p.a ≥99.0%), acetone (puriss p.a 99.5%), L-ascorbic acid (L-AA) standard solution (puriss p.a ≥90%), Trolox ((±)-6-hydroxy 2,5,7,8-tetramethylchroman-2-carboxylic acid (97%), 2,2-azinobis(3-ethyl-benzothiazoline-6-sulfonic acid) (ABTS) (activity 90–110%), potassium persulfate (puriss p.a 98%), ethanol (puriss p.a 96%), Folin–Ciocalteu reagent, chlorogenic acid (puriss p.a ≥98.0%), and sodium carbonate (puriss p.a 99%) were purchased from Sigma Aldrich, Fluk, Poch, or Linegal Chemicals.

2.2. Plant materials

The experimental materials were six varieties of potato (*Solanum tuberosum* L.). The varieties and their characteristics are shown in Table 1.

Table 1. Characteristics of the potato varieties examined in this study.

Variety	Origin of seed tubers	Skin colour	Flesh colour	Average Yield [t ha^{-1}][1]	Cooking type
Ametyst	Poland	yellow	cream	64.4	medium meal
Aruba	Poland	yellow	cream	34.4	slightly floury
Ingrid	Netherlands	yellow	light yellow	41.2	slightly floury
Flaming	Poland	red	light yellow	33.3	slightly floury
Altesse	France	yellow	yellow	44.9	intermediate type
Elanda	Poland	yellow	yellow	44.0	slightly floury

[1]Characteristics from the *National Register of Varieties of Potato ed. XV*

Potatoes were grown in experimental fields at the experimental station of the Plant Breeding and Acclimatization Institute, Research Division Jadwisin, Poland. Agronomic inputs used in conventional systems are shown in Table 2.

Table 2. Agronomic inputs used in conventional systems.

Crop production practice	Conventional system
Fertilisation	4–5 t ploughed rye straw + 1 kg mineral nitrogen per 100 kg straw + mustard as a catch crop; N: 100 kg.ha^{-1}, P: 53 kg.ha^{-1}, K: 150 kg.ha^{-1}
Weed control	Mechanical tillage + herbicides: 2012: Afalon-1.9 l.ha^{-1}, Titus+Trend (60 g.ha^{-1} + 0.5 l.ha^{-1}) 2013: Linurex-1.8 l.ha^{-1}, Titus + Trend (60 g.ha^{-1} + 0.5 l.ha^{-1})
Colorado potato beetle control	Chemical insecticides: 2012: Actara -60 g.ha^{-1} 2013: Actara 2 times per season -70 g.ha^{-1}, Apacz-40 g.ha^{-1}
Late blight control	Chemical fungicides 2012: Ridomil-2 l.ha^{-1}, Revus-0.6 l.ha^{-1}, Ranman-0.2 l.ha^{-1}, Altima-0.4 l.ha^{-1}, Ranman-0.2 l.ha^{-1}, 2013: Revus-0.6 l.ha^{-1}

After harvest, the potato tubers (whole crop) were placed in an experimental storage room under the following conditions: 1) during the preparatory period for the first two weeks after harvest, the temperature was maintained at 15°C with 95±2% relative humidity; 2) subsequently, over a two-week period, the temperature was gradually lowered to 8°C (chamber I) or 5°C (chamber II) while maintaining the same relative humidity (95%).
Post-harvest potato samples were collected for analysis immediately after harvest (the third set of ten days [decade] of September). Post-storage samples were collected after 3 months of storage at 5°C and 8°C (the third decade of January). In each test, the samples were collected at random times (each laboratory sample consisted of ca. 50 tubers ~40 mm in size).

2.3. Sample preparation

The samples were prepared for analysis in the following manner: 1) tubers were left raw, unpeeled, and uncut; 2) uncut tubers were peeled (cut slit width 1.33 mm) and boiled in water in a beaker (standard proportions of 0.5 kg of potatoes and 0.7 dm^3 of boiling water without added salt) for approximately 15±2 min (beginning when the tubers were placed into boiling water); and 3) tubers were left unpeeled and boiled.

2.4. Measurement of dry matter

The dry matter content was determined using a two-stage drying-weighing method involving drying at 60°C for 12 hours, followed by 105°C until the sample maintained a constant weight.

2.5. Extraction of hydrophilic fractions

Freeze-dried samples were ground into a fine powder with a Freezer Mill 6770. Five grams of freeze-dried powder was vortexed for 2 min in 25 ml hexane, and the mixture was filtered through a Buchner funnel. The hexane extraction step was repeated twice, and the combined lipophilic extracts were evaporated to dryness at 50°C in a vacuum evaporator. The residue produced after hexane extraction was extracted twice in 25 ml of acidified methanol (7% acetic acid in 80% methanol) to obtain the hydrophilic fraction. The final volume of the hydrophilic fraction was adjusted to 50 ml with acidified methanol.

2.6. Measurement of ABTS radical-scavenging activity

The ABTS radical-scavenging activity of the hydrophilic fractions was determined as described by RICE-EVANS *et al*. (1997) using the modifications described by RE *et al*. (1999). The ABTS_+ solution consisted of 7 mM ABTS salt and 2.45 mM potassium persulfate (final concentration) in 25 ml of distilled water. The mixture was allowed to stand in the dark at room temperature for 12–16 h before use. The ABTS_+ solution was diluted with 95% ethanol (approximately 600 μl ABTS to 40 ml 95% ethanol) to obtain an absorbance of approximately 0.7 (±0.02) at 734 nm. Fresh ABTS_+ solution was prepared for each analysis. Antioxidant or standard solutions (20 μl) were mixed with 1 ml of diluted ABTS_+ solution and incubated at 30°C. The absorbance at 734 nm was read every minute for 30 min. Ethanol (95%) was used as a blank. Trolox (0 to 500 μM) was used as a standard. Free radical scavenging activity was expressed as μmoles of Trolox per 100 grams of sample (μmol TE·100 g^{-1}).

2.7. Measurement of total phenolics

Total phenolic contents were measured by the Folin-Ciocalteu method using the modifications described by Singleton *et al*. (1999). The hydrophilic extract (0.5 ml) was diluted with distilled water to 5 ml, to which 0.5 ml Folin-Ciocalteu reagent was added and allowed to react at room temperature for 3 min. After the addition of 1 ml of 1 N sodium carbonate, the mixture was incubated at room temperature for 1.5 h. The absorbance was measured at 725 nm using a spectrophotometer (T70+ UV/VIS) with distilled water as a blank. Chlorogenic acid was used as a standard. Total phenolic contents were reported as milligrams per gram dry matter (mg TPs·g^{-1} DM).

2.8. Measurement of L-ascorbic acid

L-ascorbic acid (AA) concentrations were measured using a standard spectrophotometric method (Polish standard PN-A04019) based on the ability of AA to reduce the dye 2,6-dichloroindophenol. Briefly, a 10-g sample of potato tuber was extracted in 0.4% oxalic acid by homogenizing the sample in an Ultra Turrax T25 for 3 min at 13,500 rpm. The extract was filtered through filter paper under a vacuum and adjusted to 100 ml with the same extraction solution. Next, 5 ml of the extract was reacted with 2 ml of 2,6-dichloroindophenol (1.6%) for 2 min. The absorbance was measured at 500 nm using a spectrophotometer (T70+ UV/VIS) with oxalic acid and 2 ml of 2,6-dichloroindophenol (1.6%) as a blank. The AA concentration was quantified via comparison with a standard curve of L-AA. The AA content was reported as milligrams per gram dry matter (mg AA·g^{-1} DM).

2.9. Statistical analysis

Two and three-way analyses of variance (ANOVAs) based on fixed model and multiple regression analysis were conducted to determine if the studied factors significantly differed from the analysed features. Significant differences between means for the objects (after confirming the existence of these differences using F-test in analysis of variance) were determined using Tukey's multiple comparison procedure with $P \leq 0.05$. Relationships (after confirming the existence of these relationships using multiple regression model analysis) were described using determination coefficients (R^2) and convergence coefficients (φ^2). Calculations were performed using Statistica software (v.12).

3. RESULTS AND DISCUSSION

3.1. Ascorbic acid (AA)

According to BURGOS *et al.* (2009), MURNIECE *et al.* (2011), HAMOUZ *et al.* (2008), and VALCALCER *et al.* (2015), the AA content in potato tubers after harvest is dependent on the variety, place of cultivation, and environmental conditions during growth. According to HAMOUZ *et al.* (2008), the AA content in raw potatoes can vary from 14 to 1.093 mg·g^{-1} DM, while according to BURGOS *et al.* (2009), it can vary from 295 to 1.677 mg·g^{-1} DM In the current study, the highest AA content was detected in potato tubers after harvest (light yellow-fleshed potato, 1.142 mg·g^{-1} DM) (Table 3).
Flesh colour significantly affected AA content in tubers. We observed significant differences in AA content between tubers with yellow-coloured flesh (1.100 mg·g^{-1} DM) and cream-coloured flesh (0.952 mg·g^{-1} DM). By contrast, HEJTMÁNKOVA *et al.* (2009) showed that white and yellow potatoes did not differ in terms of AA content, whereas HAMOUZ *et al.* (2008) determined that AA content was 2.9-times higher in red and purple potatoes than in potatoes with yellow and white flesh. VALCALCER *et al.* (2015) studied 5 potato varieties with white flesh, 7 with yellow flesh, 20 with light-yellow flesh, and 25 with cream-coloured flesh and found that the AA content in tubers is determined by both environmental conditions (location, climate) and variety. In the current study, the highest AA content was detected in raw tubers of the Altesse variety (yellow flesh) and the lowest was detected in potatoes of the Ametyst variety (cream-coloured flesh). The difference in AA content between these varieties reached 26%.

Short-term storage at both 5°C and 8°C significantly affected the AA content in raw potatoes. Potato tubers contained approximately 40% more AA immediately after harvest than potatoes stored for 3 months. Consistent with this finding, KEIJBETS and EBBENHORST-SELLER (1990) recorded AA losses of 20–60% in potatoes during the first 4 months of storage. Such patterns were also observed by ABONG *et al.* (2001), who showed that the losses of AA in raw potatoes were much higher during the first months of storage than during the final storage period. Similar studies were carried out by GRUDZIŃSKA and ZGÓRSKA (2011), who showed that in potato tubers stored through autumn (up to 90 days), AA losses reached 10%, while in potatoes stored through winter (up to 150 days), AA losses reached 22%. RIVERO *et al.* (2003) showed that the reductions of AA levels after 20 weeks of storage (140 days) reached 50% in some varieties. We found that AA contents were significantly lower in tubers stored at 5°C (0.702 $mg \cdot g^{-1}$ DM) vs. 8°C (0.967 $mg \cdot g^{-1}$ DM). Similar associations were observed by KÜLEN *et al.* (2013) who recorded a loss of AA in raw potato tubers in the first months of storage at 4°C. These observations are consistent with the conclusions of SAPEI and HWE (2014), whose study on the kinetics of vitamin C degradation revealed that losses of vitamin C in products stored at lower temperatures could be reduced by the simultaneous presence of sucrose. Potatoes stored at lower temperatures accumulate this sugar GRUDZIŃSKA at el. (2016). No interactions between flesh colour and the time of tuber storage in relation to storage temperature have been demonstrated.

Statistical analysis of our results revealed that boiling had a significant effect on AA contents in potato tubers (Table 4). The greatest changes in AA content were observed in boiled potatoes directly after harvest (~40% loss of AA), while the smallest changes were observed in boiled potatoes after 3 months of storage at 5°C.

In addition, peeling tubers before thermal processing increased the losses of AA by approximately 7%. Peeling had a significant effect on the AA content in boiled tubers with cream-coloured flesh after harvest (peeled 0.715 $mg \cdot g^{-1}$ DM; unpeeled 0.466 $mg \cdot g^{-1}$ DM) and in yellow-coloured potatoes (peeled 0.607 $mg \cdot g^{-1}$ DM; unpeeled 1.009 $mg \cdot g^{-1}$ DM). These differences were not observed in tubers that were boiled after storage. Similar association were noted by RYTEL and LISIŃSKA (2007). LACHMAN *et al.* (2013) detected significant losses (up to 69%) of AA in boiled peeled potatoes compared to raw tubers. In the current study, such large differences were not observed. The greatest differences between AA losses were recorded after harvest in potatoes with yellow and light-yellow flesh that were peeled and boiled (44% and 46%, respectively).

Statistical analysis of the results revealed significant interactions between flesh colour, cooking, and storage (Table 4). The lowest AA content was detected in unpeeled boiled potatoes with cream-coloured flesh after harvest (0.466 $mg \cdot g^{-1}$ DM), while the highest AA content was detected in unpeeled boiled yellow-coloured potatoes after harvest (1.009 $mg \cdot g^{-1}$ DM) and in peeled boiled yellow-coloured potatoes after storage at 8°C (0.955 $mg \cdot g^{-1}$ DM).

Table 3. AA content [mg g $^{-1}$ DM] in potato tubers under different treatments.

Variety	After harvest				After storage							
					5°C				8°C			
		After cooking			After cooking				After cooking			
	Raw	Unpeeled	Peeled	Mean	Raw	Unpeeled	Peeled	Mean	Raw	Unpeeled	Peeled	Mean
CREAM-COLOURED FLESH												
Ametyst	0.889	0.455	0.685	0.676^{ab}	0.695	0.540	0.615	0.616^{a}	0.840	0.800	0.740	0.793^{bc}
Aruba	1.016	0.518	0.746	0.760^{b}	0.655	0.524	0.592	0.590^{a}	0.885	0.592	0.743	0.740^{b}
Mean	*0.952*	*0.466^{A}*	*0.715^{C}*	*0.711*	*0.675*	*0.532^{B}*	*0.603^{BC}*	*0.603*	*0.862*	*0.696^{C}*	*0.741^{C}*	*0.767*
LIGHT YELLOW FLESH												
Ingrid	1.344	0.786	0.585	0.905^{cd}	0.798	0.559	0.560	0.639^{a}	0.986	0.740	0.659	0.795^{bc}
Flaming	0.941	0.482	0.647	0.690^{ab}	0.468	0.603	0.533	0.534^{a}	0.821	0.389	0.879	0.696^{ab}
Mean	*1.142*	*0.634^{BC}*	*0.616^{BC}*	*0.797*	*0.633*	*0.581^{B}*	*0.546^{B}*	*0.587*	*0.903*	*0.564^{B}*	*0.769^{C}*	*0.746*
YELLOW FLESH												
Altesse	1.147	0.830	0.614	0.863^{c}	1.014	0.705	0.624	0.781^{bc}	1.132	0.816	0.860	0.936^{d}
Elanda	1.054	1.188	0.601	0.947^{d}	0.582	0.823	0.750	0.718^{b}	1.136	0.920	1.051	1.035^{e}
Mean	*1.100*	*1.009^{E}*	*0.607^{BC}*	*0.906*	*0.798*	*0.764^{C}*	*0.687^{C}*	*0.750*	*1.134*	*0.868^{D}*	*0.955^{E}*	*0.986*
Mean	1.065	0.703	0.646		0.702	0.626	0.612		0.967	0.709	0.822	
Mean of cooked		*0.674a*				*0.619 a*				*0.765 b*		

Homogenous groups are denoted by letters (a, b, c and A, B, C). Means with different letters are significantly different.
a, b, c Means with different letters are significantly different between varieties after harvest and storage.
A, B, C Means with different letters are significantly different between varieties with different flesh colours after harvest and storage.

Table 4. Sources of variation and ANOVA results for AA content in potato tubers under different treatments (statistical analyses of the data shown in Table 3).

Sources of variation	ANOVA results					
	Sum of the squares	Degrees of freedom	Mean square	F statistic	p-value	Significance
Variety (V)	0.965	5	0.193	16.363	0.0001	***
Storage temperature (S)	0.603	2	0.302	25.562	0.0001	***
Boiling (B)	0.920	2	0.460	38.982	0.0025	**
(V) × (S)	0.382	10	0.038	3.237	0.0001	***
(V) × (B)	0.558	10	0.056	4.733	0.0001	***
(S) × (B)	0.544	4	0.136	11.518	0.0001	***
(V) × (S) × (B)	0.887	20	0.044	3.759	0.0001	***
Flesh colour (FC)	0.769	2	0.384	21.372	0.0001	***
(FC) × (S)	0.076	4	0.019	1.051	0.3861	n.s
(FC) × (B)	0.233	4	0.058	3.238	0.0162	*
(FC) × (S) × (B)	0.332	8	0.041	2.307	0.0279	*

n.s. not significant; *, significant at α=0.05; **, significant at α=0.01; ***, significant at α=0.001.

3.2. Total phenolics (TPs)

Table 5 shows the TP contents in the potato tubers under different treatments.
Flesh colour had a significant effect on TP content. The highest TP content was found in tubers with yellow flesh both after harvest and after storage (3.766 mg·g^{-1} DM after harvest to 6.350 mg·g^{-1} DM after storage). The TP content was significantly lower in tubers with cream-coloured flesh (f2.633 to 3.831 mg·g^{-1} DM) and light-yellow flesh (3.363 to 4.335 mg·g^{-1} DM). Similar results were obtained by VALCARCEL *et al.* (2015) and TIERNO *et al.* (2015).
The differences in TP contents between raw tubers with yellow- and cream-coloured flesh were 1.125 mg·g^{-1} DM for tubers after harvest, 1.268 mg·g^{-1} DM for tubers stored at 5°C, and 2.520 mg·g^{-1} DM for tubers stored at 8°C. For raw tubers with light-yellow and yellow flesh, the differences in TP contents were much lower, ranging from 0.395 mg·g^{-1} DM after harvest to 2.016 mg·g^{-1} DM after storage at 8°C. Differences in TP contents between tubers with different flesh colours (yellow, light yellow, and cream) were no greater than 33%. LACHMAN *et al.* (2008) observed much greater differences in TP contents (58%) between potato tubers with purple and yellow flesh.
Storage temperature significantly affects TP contents in tubers (GRUDZIŃSKA and ZGÓRSKA, 2011, KÜLEN *et al.*, 2013). We found that the TP content was significantly higher in tubers stored at the higher temperature (8°C) (3.830 to 6.350 mg·g^{-1} D.M) than at 5°C (2.982 to 4.250 mg·g^{-1} D.M). KUMAR and EZEKIEL (2009), GRUDZIŃSKA and ZGÓRSKA (2011), and GRUDZIŃSKA and BARBAŚ (2017) found that at high storage temperatures, tubers germinate more frequently and lose turgor. AL - WESHAHY *et al.* (2013) found that the TP content in tubers significantly decreased during the first 4 weeks of storage (regardless of temperature) and significantly increased after 8 weeks of storage. At the higher storage temperature (8°C), we observed significant variation in the

differences in TP content, with the greatest differences observed in raw tubers with light-yellow flesh (Ingrid and Flaming) and yellow flesh (Altesse and Elanda).

Table 5. TP contents [mg g $^{-1}$ DM] in potato tubers under different treatments.

Variety	After harvest				After storage							
					5°C				8°C			
	Raw	After cooking		Mean	Raw	After cooking		Mean	Raw	After cooking		Mean
		peeled	peeled			peeled	peeled			peeled	peeled	
CREAM-COLOURED FLESH												
Ametyst	2.433	3.043	2.511	2.662^{a}	2.907	5.414	4.194	4.171^{de}	3.455	4.125	3.875	3.818^{cd}
Aruba	2.834	3.242	2.461	2.845^{ab}	3.058	6.105	4.134	4.432^{ef}	4.208	4.963	3.316	4.162^{de}
Mean	*2.633*	*3.142*	*2.486*	*2.754^{B}*	*2.982*	*5.760*	*4.164*	*4.302^{CD}*	*3.831*	*4.544*	*3.595*	*3.990^{C}*
LIGHT YELLOW FLESH												
Ingrid	3.547	4.029	2.916	3.497^{bc}	3.980	6.869	4.726	5.191^{ef}	5.106	6.138	4.400	5.214^{ef}
Flaming	3.180	2.786	1.978	2.648^{a}	2.127	5.102	2.802	3.343^{bc}	3.565	4.276	2.643	3.494^{bc}
Mean	*3.363*	*3.407*	*2.447*	*3.072^{BC}*	*3.053*	*5.985*	*3.764*	*4.267^{CD}*	*4.335c*	*5.207*	*3.521*	*4.354^{CD}*
YELLOW FLESH												
Altesse	3.510	3.870	3.847	3.742^{bc}	4.316	7.067	5.904	5.762^{fg}	5.343	6.276	4.790	5.469^{ef}
Elanda	4.007	4.075	3.257	3.779^{bc}	4.184	7.747	5.118	5.683^{f}	7.363	8.938	5.047	7.116^{g}
Mean	*3.758*	*3.973*	*3.552*	*3.761^{C}*	*4.250*	*7.407*	*5.511*	*5.722^{D}*	*6.35l*	*7.607*	*4.918*	*6.292^{D}*
Mean	3.251	3.507	2.828		3.428	6.384	4.479		4.840	5.786	4.011	
Mean of cooked	*3.167 a*				*5.431 b*				*4.898 ab*			

Homogenous groups are denoted by letters (a, b, c and A, B, C). Means with different letters are significantly different.
a, b, c Means with different letters are significantly different between varieties after harvest and storage.
A, B, C Means with different letters are significantly different between varieties with different flesh colours after harvest and storage.

In unpeeled tubers, TP contents were significantly higher in cooked vs. raw potatoes, regardless of flesh colour and whether the tubers were stored or analysed after harvest. Similar results were obtained by NAVARRE *et al.* (2010) and BURGOS *et al.* (2013), who reported an increase in the contents of phenolic compounds in potato tubers after cooking, which varied depending on the method of cooking (boiling, steaming, baking). According to BLESSINGTON *et al*. (2010), the increase in TP contents in potato tubers after cooking may be related to the higher extractability of these compounds from the cooked tuber cell matrix compared to the uncooked matrix. In the current study, the greatest difference in TP content was detected between raw and unpeeled cooked tubers after storage at 5°C (2.778 to 3.157 mg·g^{-1} DM, respectively) regardless of flesh colour, and the smallest difference was detected in tubers after harvest (0.044 to 0.509 mg·g^{-1}, respectively).
Higher TP levels were observed in unpeeled boiled tubers regardless of whether they were stored at either temperature or measured immediately after harvest. TP contents were significantly lower in peeled vs. unpeeled potatoes. Similar results were obtained by LECHMANA *et al.* (2008), who measured 30.4–38.7% differences in phenolic compound

contents as a result of peeling. Similarly, DAO and FRIDMAN (1992) detected substantial amounts of phenolic compounds just below the skin to ~2 mm into the flesh of potato tubers. TIERNO *et al.* (2015) reported that peeling allows for the migration and degradation of phenolic compounds during cooking. Therefore, cooking potatoes without peeling them is an effective method for reducing the loss of phenolic compounds.
Statistical analysis of our results showed no significant interaction between the factors flesh colour, cooking, and storage (Table 6).

Table 6. Sources of variation and ANOVA results for TP content in potato tubers under different treatments (statistical analysis of the data shown in Table 5).

Source of variation	ANOVA results					
	Sum of the squares	Degrees of Freedom	Mean square	F statistic	p-value	Significance
Variety (V)	73.607	5	14.721	167.538	0.0001	***
Storage (S)	60.932	2	30.466	346.723	0.0001	***
Boiling (B)	51.210	2	25.605	291.401	0.0001	***
(V) × (S)	14.851	10	1.485	16.901	0.0001	***
(V) × (B)	7.792	10	0.779	8.867	0.0001	***
(S) × (B)	32.893	4	8.223	93.587	0.0001	***
(V) × (S) × (B)	5.495	20	0.275	3.127	0.0050	***
Flesh colour (FC)	52.628	2	26.314	55.612	0.0001	***
(FC) × (S)	7.068	4	1.767	3.734	0.0077	**
(FC) × (B)	1.796	4	0.449	0.949	0.4401	n.s
(FC) × (S) × (B)	2.821	8	0.353	0.745	0.6514	n.s

n.s., not significant; *, significant at α=0.05; **, significant at α=0.01; ***, significant at α=0.001.

3.3. Antioxidant activity

Table 7 shows changes in antioxidant activity in potato tubers under different treatments. Flesh colour had no significant effect on the antioxidant activity of raw tubers. Higher antioxidant activities were observed in potatoes with light-yellow flesh after harvest (0.589 μmol TE·g^{-1}), and lower antioxidant activities were observed in potatoes with cream-coloured flesh (0.460 μmol TE·g^{-1}), but these differences were not significant (Tables 7 and 8).
After harvest, the antioxidant activity ranged from 0.460 μmol TE·g^{-1} in cream-coloured tubers to 0.554 μmol TE·g^{-1} in tubers with yellow flesh. After 3 months of storage at both temperatures, the antioxidant activity of tubers significantly decreased by 0.264 μmol TE·g^{-1} for light-yellow tubers and 0.168 μmol TE·g^{-1} for cream-coloured tubers. Similar observations were made by ROSENTHAL and JANSKY (2008), who detected higher antioxidant activity in potato tubers directly after harvest than after storage. According to their study, antioxidant activity did not changed after up to 135 days of storage. In the current study, significant changes in antioxidant activity were observed in tubers after 90 days of storage at 5°C. At the higher storage temperature (8°C), the antioxidant activity in potatoes was similar to that after harvest.

Table 7. Antioxidant activity [μmol TE·g^{-1}] in potato tubers under different treatments.

Variety	After harvest				After storage							
					5°C				8°C			
	After cooking				After cooking				After cooking			
	Raw	Unpeeled	Peeled	Mean	Raw	Unpeeled	Peeled	Mean	Raw	Unpeeled	Peeled	Mean
CREAM-COLOURED FLESH												
Ametyst	0.553	0.348	0.442	0.447 *bc*	0.145	0.354	0.267	0.255 *a*	0.557	0.388	0.496	0.480 *c*
Aruba	0.429	0.718	0.294	0.480 *c*	0.240	0.354	0.395	0.329 *a*	0.496	0.685	0.321	0.500 *cd*
Mean	*0.481^{C}*	*0.533^{D}*	*0.368^{B}*	*0.460*	*0.192^{A}*	*0.354^{B}*	*0.331^{B}*	*0.292*	*0.526^{CD}*	*0.538^{D}*	*0.408^{BC}*	*0.490*
LIGHT YELLOW FLESH												
Ingrid	0.678	0.990	0.348	0.672 *d*	0.297	0.111	0.476	0.294 *a*	0.462	0.449	0.233	0.380 *b*
Flaming	0.456	0.641	0.405	0.500 *cd*	0.432	0.294	0.347	0.357 *ab*	0.307	0.429	0.503	0.413 *bc*
Mean	*0.567^{D}*	*0.815^{E}*	*0.376^{B}*	*0.589*	*0.362^{B}*	*0.202^{A}*	*0.411^{BC}*	*0.325*	*0.384^{CD}*	*0.439^{D}*	*0.368^{BC}*	*0.397*
YELLOW FLESH												
Altesse	0.440	0.523	0.532	0.498 *c*	0.294	0.381	0.321	0.332 *ab*	0.350	0.510	0.489	0.449 *bc*
Elanda	0.746	0.577	0.510	0.611 *d*	0.415	0.361	0.422	0.399 *b*	0.658	0.617	0.368	0.547 *cd*
Mean	*0.593^{D}*	*0.550^{D}*	*0.521^{CD}*	*0.554*	*0.354^{B}*	*0.371^{B}*	*0.371^{B}*	*0.365*	*0.504^{CD}*	*0.563^{D}*	*0.428^{C}*	*0.498*
Mean	0.550 *b*	0.632 *c*	0.421 *ab*		0.303 *a*	0.309 *a*	0.371 *a*		0.471*b*	0.513*b*	0.401*ab*	
Mean of cooked	*0.527 c*				*0.340 a*				*0.457 b*			

Homogenous groups are denoted by letters (a, b, c and A, B, C). Means with different letters are significantly different.
a, b, c Means with different letters are significantly different between varieties after harvest and storage.
A, B, C Means with different letters are significantly different between tubers with different flesh colours after harvest and storage.

Table 8. Sources of variation and ANOVA results for antioxidant activity in potato tubers under different treatments (statistical analysis of the data shown in Table 7).

Sources of variation	ANOVA results					
	Sum of the squares	Degrees of freedom	Mean square	F statistic	p-value	Significance
Variety (V)	0.164	5	0.033	156.747	0.0001	***
Storage (S)	0.788	2	0.394	1876.919	0.0001	***
Boiling (B)	0.135	2	0.068	322.795	0.0001	***
(V) × (S)	0.252	10	0.025	120.186	0.0001	***
(V) × (B)	0.309	10	0.031	147.103	0.0001	***
(S) × (B)	0.245	4	0.061	291.976	0.0001	***
(V) × (S) × (B)	0.705	20	0.035	168.099	0.0001	***
Flesh colour (FC)	0.063	2	0.031	2.778	0.6810	n.s
(FC) × (S)	0.149	4	0.037	3.303	0.0147	**
(FC) × (B)	0.016	4	0.345	0.345	0.8471	n.s
(FC) × (S) × (B)	0.304	8	3.379	3.379	0.0022	**

n.s., not significant; *, significant at α=0.05; **, significant at α=0.01; ***, significant at α=0.001.

The cooking of peeled tubers led to a decrease in antioxidant activity regardless of flesh colour and storage condition. The antioxidant activity was significantly higher in cooked unpeeled tubers (0.632 μmol TE·g^{-1}) than in raw potatoes after harvest (0.550 μmol TE·g^{-1}) and after storage at 8°C (0.512 μmol TE·g^{-1}).
According to BLESSINGTON *et al.* (2010), PERLI *et al*. (2012), and LACHMAN *et al.* (2013), cooking changes the antioxidant activity in tubers. These changes depend on the cooking method and pre-treatment of potatoes (peeling). As a result of peeling, the contents of the phenolic compounds flavonoids, flavones, anthocyanins, and lutein in potato tubers decreased by approximately 46–54%, leading to a significant reduction in antioxidant activity in tubers after cooking (PERLA *et al.*, 2012). NARA *et al*. (2006) indicated that potato tuber peels have high antioxidant activity, suggesting they could be used as a new source of natural antioxidants.
Statistical analysis of our results revealed a significant effect of variety on antioxidant activity (Table 8). The highest antioxidant activity was detected in raw tubers of the Elanda variety directly after harvest (0.748 μmol TE·g^{-1}) and in unpeeled cooked tubers of the Aruba variety (0.718 μmol TE·g^{-1}), while the lowest antioxidant activity was detected in raw tubers of the Ametyst variety (0.145 μmol TE·g^{-1}) after storage at 5°C and in unpeeled cooked tubers of the Ingrid variety (0.111 μmol TE·g^{-1}).

3.4. Correlation analysis

The correlation between phenolic compound content and antioxidant activity is widely known (LACHMAN *et al.*, 2008, REYES *et al.*, 2005, RUMBOA *et al.*, 2009, TEOW *et al.*, 2007, NZARAMBA *et al.*, 2013). The correlation coefficients between the parameters examined in the above-mentioned studies ranged from 0.430 (TEOW *et al.*, 2007, AL-WESHAHY *et al.*, 2013) to 0.930 (REDDIVARI *et al.*, 2007), with the size of the coefficient

depending on the research material, crop location, and climatic conditions during the growing season.
Table 9 shows the coefficient of determination and convergence coefficient between antioxidant activity and the AA and TP contents depending on flesh colour. The coefficient of determination between (AA) × (TE) in raw potatoes ranged from $R^2 = 0.563$ for light-yellow tubers to $R^2 = 0.737$ for yellow tubers.

Table 9. Determination and convergence coefficients between antioxidant activity (TE) and L-ascorbic acid (AA) and total phenolic compounds (TP) contents in raw, unpeeled, and peeled potatoes after cooking depending on flesh colour.

Flesh colour	(AA)×(TE)			(TPs)×(TE)		
	Raw	Unpeeled	Peeled	Raw	Unpeeled	Peeled
	Determination coefficient (R^2)					
Cream	0.688^{***}	0.758^{***}	0.743^{***}	$0.109^{n.s}$	$0.019^{n.s}$	$0.182^{n.s}$
Light yellow	0.563^{**}	$0.277^{n.s}$	0.702^{***}	0.646^{**}	0.781^{***}	$0.266^{n.s}$
Yellow	0.737^{***}	$0.197^{n.s}$	0.613^{**}	0.793^{***}	0.669^{***}	$0.399^{n.s}$
	Convergence coefficient (ϕ^2)					
Cream	31.2	24.2	25.7	89.1	98.1	81.8
Light yellow	43.7	72.3	29.8	35.4	21.9	73.4
Yellow	26.3	80.3	38.7	20.7	33.1	60.1

n.s., not significant; *, significant at α=0.05; **, significant at α=0.01; ***, significant at α=0.001.

In unpeeled cooked tubers, significant dependencies ($R^2 = 0.758$) were observed only in tubers with cream-coloured flesh. In potatoes with yellow and light-yellow flesh, such relationships were not observed ($R^2 = 0.197$; $R^2 = 0.277$, respectively). Other dependencies were observed for peeled cooked potatoes: regardless of flesh colour, the determination coefficients were statistically significant (0.613 to 0.743). The highest convergence of features was observed for peeled and unpeeled cooked tubers with cream-coloured flesh (24.2 and 25.7%, respectively).
Different relationships were obtained for the (TPs) × (TE) model. For cream-coloured tubers, the determination coefficient (R^2) was not statistically significant (0.019 for unpeeled cooked tubers to 0.182 for peeled cooked tubers). The convergence coefficient ranged from 98 to 81%, indicating that the antioxidant activity in cream-coloured tubers was shaped by other factors and not by TP content. Non-significant relationships (0.182 to 0.399) were also obtained for peeled cooked tubers irrespective of flesh colour. These results are consistent with the finding of DAO and FRIDMAN (1992) that significant amounts of phenolic compounds are present just below the peel to ~2 mm of the potato tuber.
SEIJO-RODRÍGUEZ *et al.* (2018) found that due to the high correlation between TP content and antioxidant activity, TP content could be used as an indicator of the antioxidant activity of a tuber. Our findings do not fully confirm this notion, as this indicator could be determined only in raw and unpeeled cooked tubers but would be difficult to determine using peeled cooked tubers due to the different level of phenolic compound accumulation under the peel.

Fig. 1 shows the relationship between the contents of AA and TPs and antioxidant activity in raw tubers and in unpeeled and peeled cooked tubers regardless of flesh colour. The higher the AA content in boiled peeled potatoes, the higher the antioxidant activity (Fig. 1).

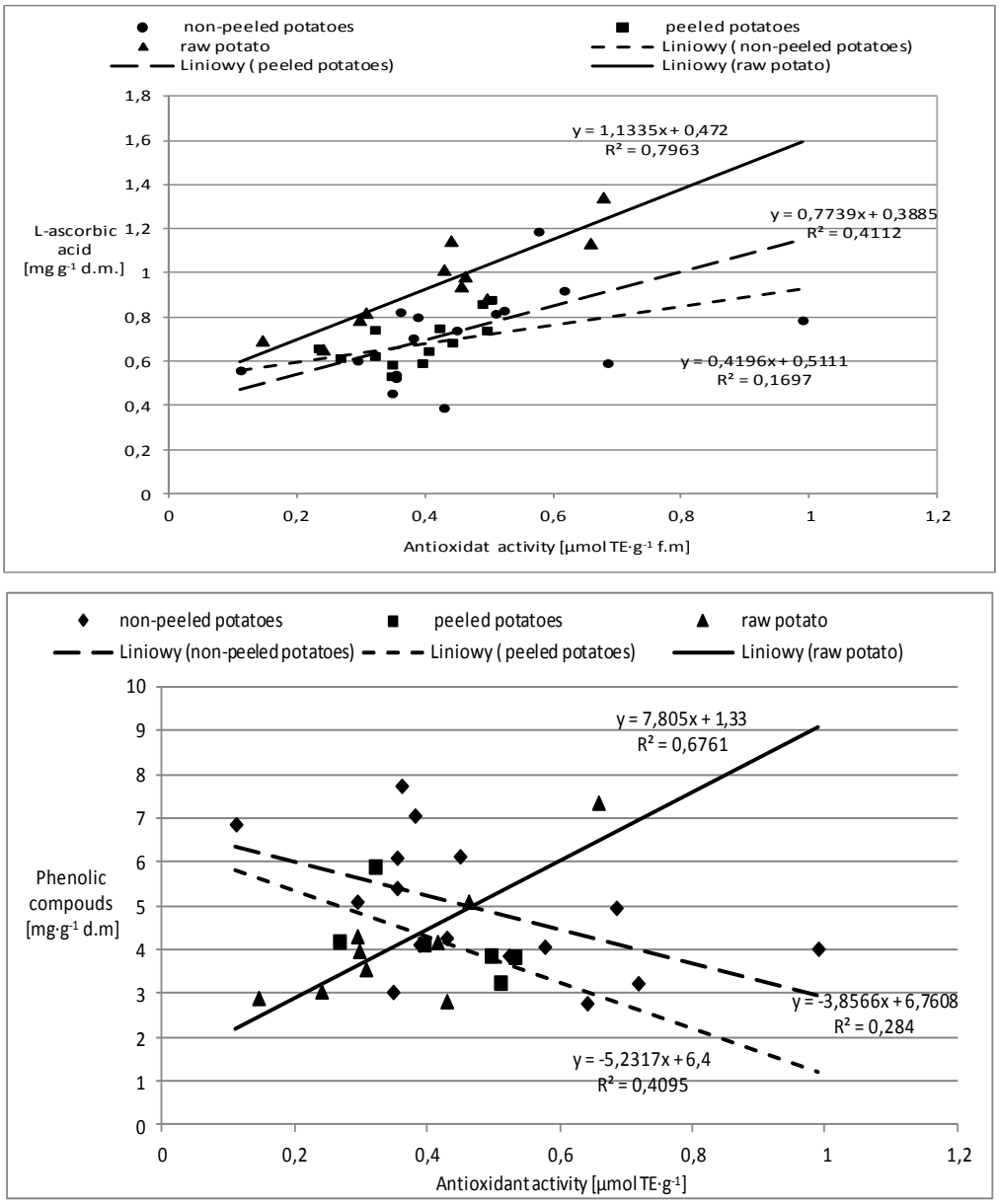

Figure 1. The relationship between antioxidant activity and the contents of L-ascorbic acid and total phenolic compounds in raw potatoes and in unpeeled and peeled potatoes after cooking.

The correlation coefficient between antioxidant activity and AA content for peeled boiled potatoes was $R^2 = 0.411$. HEJTMÁNKOVÁ *et al.* (2009) did not detect a significant correlation between AA content and antioxidant activity ($R^2 = 0.08$) in unpeeled raw potatoes. We obtained similar results, but our results were for unpeeled boiled potatoes (R^2

= 0.169). The highest correlation for AA content and antioxidant activity was obtained for raw tubers (R^2 = 0.796).
In the current study, the correlation between the content of TP compounds and antioxidant activity was inversely proportional in boiled potato tubers (Fig. 1): the lower the TP content, the higher the antioxidant activity. A similar relationship was detected by RUMBOA *et al.* (2009) (R^2 = 0.56). Such irregularities might indicate that the antioxidant activity in tubers after boiling is also shaped by other bioactive compounds.
There was a significant dependence between TP content and antioxidant activity in potatoes after boiling for unpeeled cooked tubers. In peeled cooked tubers, such relationships were not observed (R^2 = 0.023) (Fig. 1B). AL-WESHAHY and RAO (2009) showed that phenolic compound levels are often higher just below the peel of potato tubers than deeper inside the tuber, but this depends on the variety and the colour of the peel itself. However, according to NARA *et al.* (2006), phenolic compounds found in the peel (in both free and bound form) show high antioxidant activity, whereas those in the flesh show low antioxidant activity.

4. CONCLUSIONS

Here we demonstrated that flesh colour has a significant effect on AA and TP contents in tubers. The difference between the AA contents was 12.5% in cream- vs. yellow-coloured tubers and 16.5% between cream- and light-yellow-coloured tubers. Differences in TP contents between potatoes with different flesh colours did not exceed 33%. Significant AA loses were found in peeled boiled yellow and light-yellow tubers after harvest (44 and 46%, respectively). Significant interactions were observed between AA contents and flesh colour, boiling, and storage.
Both storage treatments significantly decreased the antioxidant activity of tubers irrespective of flesh colour. Boiling significantly decreased antioxidant activity in peeled tubers regardless of flesh colour and storage treatment. Unpeeled boiled tubers had significantly higher antioxidant activity than raw tubers after harvest. Regardless of flesh colour, high correlations were observed between (AA) × (TE) for peeled boiled tubers. Significant R^2 values were observed between (TPs) × (TE) for raw and unpeeled boiled light-yellow and yellow tubers. The relationship between TP content and TE in potatoes after boiling was significant for unpeeled tubers. The greatest matching of the model characteristics of the interdependence of features (ϕ^2) was 75% for the model (AA) × (TE) and 80% for the model (TPs) × (TE).

ABBREVIATIONS

AA - ascorbic acid.
DM - dry matter.
TPs - total phenolics.
TE - antioxidant activity, Trolox equivalents.

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