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The Physico-Chemical and Sensory Characteristics of Coloured-Flesh Potato Chips: Influence of Cultivar, Slice Thickness and Frying Temperature

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Abstract: Coloured potato chips, due to a higher concentration of bioactive compounds, may be healthier compared to traditional chips. This study examined the effect of cultivar and different slice thicknesses and frying temperatures on the physico-chemical and sensory characteristics of coloured potato chips. Potatoes chips were prepared from three coloured potato cultivars. Frying experiments were conducted at 160 and 180 °C using potato slices with thicknesses of 1.00 and 2.00 mm. The quality of the raw potatoes tubers and chips were estimated. A principal component analysis was applied to describe the differences in the physico-chemical characteristics between the potato chip samples processed with different conditions. The results showed that, significantly (p < 0.05), the highest amounts of total phenolic content, total anthocyanins, dry matter and starch were accumulated in raw tubers of potato cv. Blaue Anneliese. The highest amount of total phenolic content and anthocyanins was found in 1 mm chips of cv. Blaue Anneliese fried at 160 °C. An increased frying temperature significantly (p < 0.05) decreased the content of these compounds. The amount of fat in the chips was higher when they were fried at 160 °C than at 180 °C. Chips processed from potatoes cvs. Blaue Anneliese and Rosemarie showed a typical colour as a raw material. The hardness of the chips significantly (p < 0.05) increased with an increase in slice thickness. The flavour, odour and colour of the 1 mm chips of cv. Blaue Anneliese fried at 180 °C gained the highest rating.

Keywords: coloured-flesh potato; chips; anthocyanins; phenolic; fat content; hardness; colour

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1. Introduction

Coloured-flesh potatoes are an excellent source of some health-promoting compounds, such as phenolic compounds with characteristic anthocyanins. Therefore they are relevant components of the human diet. In addition, they are rich in carbohydrates, proteins with high biological values, vitamins and mineral elements [1–3]. According to the literature, the concentrations of phenolic compounds found in purple- and red-fleshed potatoes are a few times higher as compared to traditional, light-fleshed tubers [4]. In addition, these potatoes have attracted attention from scientists and industry, as well as consumers, due to their more attractive colour compared to potatoes with a yellow or white colour of flesh [5].

Potato chips are a very popular potato snack and are consumed all around the world. They are prepared by frying thin slices of potato in oil or fat [6]. Coloured potato chips prepared from potato cultivars with red and purple flesh are a novel alternative product to traditional potato chips. Due to the higher content of phenolic compounds, such as anthocyanins, red- and purple-flesh potato chips may be healthier compared to traditional potato chips [7].

Potato tubers for processing of chips have special quality demands compared with ware potatoes. They must contain low amounts of reducing sugars to avoid the formation of melanoidins resulting from the Maillard reaction [8]. During harvesting, storage and processing conditions, sucrose is also an important parameter, as it is the substrate of the reducing sugars that may be hydrolysed in suitable environmental conditions, ultimately leading to an increase in the sugars [9]. Acrylamide, a potentially carcinogenic compound, is formed in potatoes at high frying temperatures, and the main precursors leading to its formation are reducing sugar and amino acids, especially asparagine. Therefore, the acrylamide content in potato chips may vary depending on the chemical composition (especially the reducing sugar content) of the tubers used [10,11]. The content of sugars in potato tubers is influenced by cultivar, maturity of the tubers at harvest, the effect of year and, very importantly, storage temperature [12]. Potato tubers stored at a higher temperature (8–10 °C) do not accumulate sugars. However, after the storage of tubers at a low temperature (2–3 °C), an increase in reducing sugar content is found [13]. The amounts of dry matter and starch in potatoes also are important factors that affect the quality of chips. Higher amounts of these compounds in tubers increase crispy-consistency, chip yield, and reduce fat absorption during frying [14]. According to the literature, the dry matter and starches of potatoes varied with genotype. The change in these parameters is undoubtedly a heritable characteristic, but it is also affected by storage conditions and environmental factors [15,16]. Therefore, it is important to choose potato cultivars with acceptable tuber qualities for processing chips. After harvesting, starch content is the highest and, due to storage, gradually decreases. Starch content is proportional to the dry matter content of tubers [17].

The quality characteristics of chips also depends on the processing methods and conditions. The technological process of the production of traditional and coloured potato chips has an effect on the amounts of total phenolic content and anthocyanins of potato snacks. The phenolic compounds, especially anthocyanins, in potatoes are sensitive and may be affected by different processing steps, such as frying temperature [7]. A very important quality parameter of potato chips is the content of fat absorbed during frying process. The fat content of chips varies between 35 and 45% in total and can be 1/3 or more of the total weight [18]. According to the literature, the cultivar characteristics, slice thickness, frying temperature and time affect the absorbed fat content in potato products, such as chips [19–22]. Pedreschi et al. [23] reported that frying at 120 °C produced potato chips that were crispier and contained more fat than potato chips fried at 180 °C. Paunović et al. [20] also found that the slice thickness and the surface area of the potato had a significant effect on fat uptake. According to these authors, potato slices with a larger surface area absorbed a higher fat content.

The main physical (colour and texture) and sensory characteristics of potato chips also depend on many factors, such as cultivar, storage conditions prior to processing, slice thickness, time and temperature of frying [19,24]. The sensory characteristics of potato chips, such as flavour, aroma, texture and colour, are considered the most important. The colour of potato chips is the first quality parameter evaluated by consumers and it can be influenced by the chemical composition of raw potatoes and the conditions of processing [25]. The colour of chips should be without brown discoloration, black streaks, or stains [26]. The texture of potato chips has a dominant contribution to the overall quality, as well as acceptability. Chips prepared from tubers with a low content of dry matter are described by sticky and fatty textures, whereas chips made of tubers rich in dry matter (above 25%) can have hard and unacceptable textures [27]. Potato flavour results from the combination of taste, aroma, and texture. During frying, flavour precursors (mainly sugars, lipids and aminos) react to produce the Maillard reaction compounds and the sugar and lipid degradation products that contribute to the flavour. In potato chips, flavour compounds are also derived from the frying oil [28,29]. The aroma of potato chips should be typical potato and oil, with no noticeable aftertaste or smell of burning and rancid fat [30].

Some studies evaluated the effect of slice thickness and frying temperature on the colour, texture and fat absorption of chips made from white- or yellow-fleshed potato cultivars. The results of these studies showed that the above-mentioned factors influenced the physical and chemical characteristics of traditional potato chips [19–22]. This demonstrated the need for potato chip manufacturers to suitably select cultivars and processing parameters. Therefore, it is interesting to determine how cultivars and different slice thicknesses, as well frying temperatures, influence the amount of total phenolic content, anthocyanins, fat uptake, colour, texture and some sensory attributes of red- and purple-flesh potato chips.

2. Materials and Methods

2.1. Plant Materials

Red-fleshed cv. Rosemarie (maturity time: medium early), dark-purple-fleshed potato cv. Blaue Anneliese (maturity time: late) and light-purple-fleshed potato cv. Valfi (maturity time: medium early) were used. Potatoes were grown in 2018 at a farm in the Anykščiai district of Lithuania (latitude, 55°39′29″N; longitude, 25°19′01″E) using standard agronomic practices. The potatoes were fertilized with NPK (14:7:17) fertilizers (800 kg ha^{-1}) at planting. The tubers were planted during the first ten day period of May and harvested at their chemical maturity in September. The climate conditions during the potato growing season 2018 are shown in Table 1.

Table 1. Air temperature and rainfall during the potato growing season in 2018.

Years	Months					
	April	**May**	**June**	**July**	**August**	**September**
Air temperature (°C)						
2018	10.3	17.0	17.3	19.5	19.1	14.6
The standard rate of climate (SRC) *	7.0	12.8	15.7	18.0	17.1	12.0
Rainfall (mm)						
2018	42.5	27.3	16.0	107.7	65.4	57.0
The standard rate of climate (SRC) *	43	57	73	89	75	66

* The standard rate of climate (SRC) is a 30 year average from 1981 to 2010.

Harvested mature tubers were cured at 17 ± 2 °C and 85–90% relative humidity for 7 days. Then potatoes were stored for two weeks at 10 °C (the relative humidity was 85–90%) until processing.

2.2. Potato Chip Preparation

Twenty physiologically and mechanically unimpaired tubers were randomly sampled from each cultivar for the production of each treatment of chips. Each treatment was replicated four times. The three-factor experiment was performed: factor A—tubers of three potato cultivars (Rosemarie, Blaue Anneliese and Valfi), factor B—different slice thicknesses (1 mm and 2 mm) and factor C—different frying temperatures (160 and 180 °C). Unpeeled coloured-flesh potatoes were washed and cut into slices of 1 mm and 2 mm thicknesses using a hand vegetable slicer. Each size of potato slices was then washed in cold water, superficially dried with paper towels and fried in refined rapeseed oil at temperatures of 160 and 180 °C for 3–5 min.

2.3. Proximate Analysis

For the qualitative analysis, 5 kg of raw potato tubers were randomly selected from each cultivar. A one-factor experiment with four designed replications was conducted. Potato tubers were analysed for dry matter by drying samples at a temperature of 105 °C to a constant weight [31], and starch was measured using a polarimetric method with a stationary digital automatic polarimeter [32]. The content of reducing sugars in the potato tubers was determined using a standard enzymatic assay (Second Method) set out by Al-Mhanna [33]. The results were expressed in grams per 100 g of dry matter (g 100 g^{-1} DM).

2.4. Sample Preparation for Total Phenolic Content and Anthocyanin Determination

Raw potato tubers and chips were analysed for the amount of total phenolic content and total anthocyanins. Raw potatoes were washed, dried, cut into slices approximately 1 cm thick and frozen at −35 °C. Then, the samples were lyophilized using sublimator (ZIRBUS Technology GmbH, Bad Grund, Germany). Next, the samples were powdered with a knife mill (Grindomix GM 200, Retsch GmbH, Haan, Germany) and stored in airtight plastic bags in the refrigerator. Potato chips were defatted using petroleum ether (Honeywell research chemicals, Seelze, Germany) by the Soxhlet extraction method (Section 2.6) and stored in airtight plastic bags at room temperature until analysed.

Determination of Total Phenolic Content

The total content of phenolic compounds was measured by the spectrophotometric method using the Folin–Cioalteu reagent [34]. First, 0.25 g of freeze-dried potato tubers or grounded defatted potato chips were mixed with 10 mL of ethanol (70% v/v) and extracted in an ultrasonic bath for 30 min. Then, the extract was centrifuged at 3000 rpm for 30 min. Next, 0.2 mL of the prepared extract was mixed with 1 mL of the Folin–Ciocalteu reagent, 0.8 mL of sodium carbonate (7%) and 5 mL of pure water. After 60 min of incubation at 20 °C in the dark, the absorbance was measured at 760 nm using a spectrophotometer (Labomed Inc., Los Angeles, CA, USA). The total phenolic content was measured with the calibration curve using gallic acid equivalent standards. The results were expressed in milligrams per gram of dry matter (mg GAE g^{-1} DM).

2.5. Determination of Total Anthocyanins Content

The total amount of anthocyanin was measured by the spectrophotometric method. First, 5 g of freeze-dried potato tubers or grounded defatted potato chips were extracted with 90 mL of methanol (50% v/v) in an ultrasonic bath at 40 °C for 30 min. Then, the solution was filtered and brought to a 100 mL volumetric flask by washing the extract with the same solvent. Next, 0.5 mL of this resulting solution is added over 10 mL of 0.1% hydrochloric acid in methanol. The absorbance was read at 528 nm. The amount of total anthocyanins was expressed as cyanidin-3-glucoside equivalent. The absorption of these pigments was determined using a spectrophotometer (Labomed Inc., Los Angeles, CA, USA). The results were expressed in milligrams per gram of dry matter (mg g^{-1} DM).

2.6. Determination of Total Fat Content

The total fat content in potato chips was measured by the Soxhlet extraction method. The analysis was conducted using a Soxhlet apparatus SOXTHERM (Gerhardt, GmbH & Co, Königswinter, Germany), where 2 g potato chips were extracted, with petroleum ether (Honeywell research chemicals, Seelze, Germany) used as a solvent [35].

2.7. Colour of Fresh Potato Tubers and Chips

The colour of raw potato tubers and chips was determined with a spectrophotometer ColorFlex (Hunter Associates Laboratory Inc., Reston, VA, USA) using the CIE Lab system [36]. The values of coordinates L* (lightness–darkness), a* (redness–greenness) and b* (yellowness–blueness) were measured. The spectrophotometer was standardized with white and black tiles. Five raw tubers of each cultivar and five ground chips were analysed, and four readings were performed to obtain an average reading.

2.8. The Texture of Potato Chips

The texture of potato chips was evaluated using a texture analyser TA.XT plus (Stable Micro Systems, Godalming, England) [37]. The hardness (N) of the chips was determined using a spherical ball probe P/5S with 5 mm diameters. The test settings were: type of test, compression; target mode, distance; distance, 3.0 mm and test speed, 1 mm/s. Each measurement was performed on 10 potato chips.

2.9. Evaluation of Sensory Quality

The sensory evaluation of potato chips was performed by a 15 member semi-trained panel, consisting of students and academic staff members of the Department of Plant Biology and Food Science. Most of the semi-trained panel (80%) were female, 46% were 22–25 years old and 34% 35-42 years old. The remaining 20% were males from the ages of 22 to 30 years. The sensory attributes, such as flavour, odour, colour and texture of potato chips, were evaluated on a 5-point scale (a score of 1 was most disliked and a score of 5 was most liked) [30]. The chip samples were identified by code numbers and presented randomly to the panellists.

2.10. Statistical Analysis

The data of raw potato tubers were statistically evaluated by a one-way analysis of variance (ANOVA) (factor A: cultivar). The data of potato chips were evaluated by a three-way ANOVA (factor A: cultivar, factor B: different slice thicknesses and factor C: different frying temperatures). For each cultivar and each treatment of chips, the analysis was preformed in triplicate and the arithmetic means were calculated. The least significant difference at a 95% probability level was estimated using the Fisher's LSD test ($p < 0.05$). A correlation-regression analysis was carried out to determine the strength and nature of the correlation between the colour coordinates L* and b* and the amounts of total phenolic content and total anthocyanins. A principal component analysis (PCA) was performed to evaluate the relationships between the different cultivars and slice thicknesses, as well frying temperatures and physico-chemical characteristics (total phenolic content, total anthocyanins, total fat content, colour coordinates L*, a* and b* and hardness) with XLSTAT software (XLSTAT, 2018, New York, NY, USA).

3. Results and Discussion

3.1. The Chemical and Physical Characteristics of Raw Potato Tubers

The proximate composition, total amounts of phenolic content and anthocyanins and colour parameters in raw potato tubers are presented in Table 2. The highest amount of dry matter was determined for cv. Blaue Anneliese (p <0.05), followed by the cvs. Valfi and Rosemarie at 21.44, 19.59 and 18.00 g 100 g^{-1}, respectively. According to the literature, the recommended percentage of dry matter in tubers for chip manufacturing is from 20 to 25% [7]. Therefore, it can be stated that the tubers of cv. Blaue Anneliese had an optimal amount of dry matter. Dry matter is one important quality parameter that affects the quantity of fat and the texture (hardness and crispiness) of the different processed potato products, such as chips and French fries, as well as the processing efficiency [19,38].

Table 2. The proximate composition and colour parameters of raw potato tubers with coloured flesh.

Quality Parameters	Potato Cultivar			p-Value
	Blaue Anneliese	Valfi	Rosemarie	
	Flesh Colour			
	Dark Purple	Light Purple	Light Red	
Dry matter (g 100 g^{-1})	21.44 ^{a}	19.59 ^{b}	18.00 ^{c}	0.013
Starch (g 100 g^{-1} DM)	89.56 ^{a}	71.03 ^{b}	76.05 ^{b}	<0.001
Reducing sugars (g 100 g^{-1} DM)	0.54 ^{b}	0.88 ^{a}	0.59 ^{b}	0.004
Total phenolic content (mg g^{-1} DM)	19.11 ^{a}	17.40 ^{b}	14.18 ^{c}	<0.001
Total anthocyanins content (mg g^{-1} DM)	5.70 ^{a}	2.74 ^{b}	2.66 ^{b}	<0.001
Colour parameters				
L*	29.78 ^{c}	48.83 ^{b}	56.81 ^{a}	<0.001
a*	15.48 ^{a}	11.30 ^{b}	15.42 ^{a}	0.002
b*	−8.16 ^{c}	−5.53 ^{b}	12.39 ^{a}	<0.001

Different letters in the same line represent significant differences among averages at $p < 0.05$. DM: dry matter.

It was established that the starch content ranged between 71.03 and 89.56 g 100 g^{-1} DM (14.23 and 19.41 g 100 g^{-1} FM), with the highest amounts in late cv. Blaue Anneliese and the lowest in medium early cv. Rosemarie and cv. Valfi tubers. The results coincide with the results of Sogut and Ozturk [39]. According to these authors, the most important factors responsible for variation in starch content are the genetic features of a cultivar and its maturity. Potatoes of early-maturing cultivars tend to have lower starch contents than late main-crop cultivars. In addition, weather (temperature and especially the amount of precipitation) and growing conditions (phosphorus and nitrogen fertilization) also affect the amounts of dry matter and starch in potato tubers [40-42]. Das et al. [43] stated that starch content could influence on the quality of potato chips. They found that the hardness of potato chips was directly related to the starch content of tubers. According to the recommendations of researchers, the starch content of potatoes for chip production should be not less than 14–17% FM [12].

The potato-specific requirements for chip production also include reducing sugar content. The optimum amount of reducing sugars in potatoes should be up to 0.2% FM [42]. Cv. Valfi tubers showed the highest amount of reducing sugars: 0.88 g 100 g^{-1} DM (0.18 g 100 g^{-1} FM). Cvs. Blaue Anneliese and Rosemarie demonstrated similar reducing sugar contents: 0.54 and 0.59 g 100 g^{-1} DM, respectively (0.12 and 0.11 g 100 g^{-1} FM, respectively). These results exhibited that all tested cultivars contained the right amount of reducing sugars. A high amount of reducing sugars (glucose and fructose) induces negative changes (darkening and off flavours) of the processed potato products during frying [44].

Dark-purple-fleshed cv. Blaue Anneliese tubers reached the highest amount of total phenolic content (19.11 mg g^{-1} DM), while cv. Rosemarie tubers with light red flesh contained the lowest amount (14.18 mg g^{-1} DM). Concerning the anthocyanins, significantly, the highest amount was also found in tubers of the cv. Blaue Anneliese (5.70 mg g^{-1} DM). The total anthocyanin contents were similar among light-purple-fleshed Valfi (2.74 mg g^{-1} DM) and light-red-fleshed Rosemarie cvs. (2.66 mg 100 g^{-1} DM). Likewise, earlier studies indicated that dark purple potato cultivars were richer sources of phenolics and anthocyanins than light purple or red potato cultivars [5,45]. Hamouz et al. [45] evaluated the amounts of total phenolic content in potato tubers of eight cultivars with purple and red flesh and found that the amount ranged from 19.4 to 25.9 mg g^{-1} DM. In that study, the highest phenolic content was observed in two cultivars with dark purple flesh, Vitelotte and Violette (25.9 and 25.8 mg g^{-1} DM, respectively). Previous research showed that, the total anthocyanin content ranged from 1.48 to 4.97 mg g^{-1} DM in coloured potatoes. The dark purple cultivars demonstrated the highest total anthocyanin content [46].

Recently, potato tubers with purple and red flesh have attracted the attention from consumers, due to their more attractive colour. The colour of these potatoes depends on the amount and composition of anthocyanins, as well as ongoing enzymatic darkening. The highest L* (lightness) value was determined for cv. Rosemarie and the lowest for cv. Blaue Anneliese tubers (Table 2). Tubers of cv. Blaue Anneliese were the bluest (b*—−8.16), followed by the cv. Valfi (b*—−5.53). The tubers of cv. Rosemarie showed the highest a* values (red colour).

3.2. The Chemical Characteristics of Coloured-Flesh Potato Chips

A three-way ANOVA revealed significant variations in total phenolic content, depending on the cultivar, slice thickness, frying temperature and their interaction (Table 3). The amount of total phenolic content in the potato chips ranged from 10.86 to 3.66 mg g^{-1}. Potato cultivar differences significantly influenced the amount of phenolic content; it was the highest in chips of cv. Blaue Anneliese (10.86–6.98 mg g^{-1}), followed by cvs. Valfi (7.46–3.85 mg g^{-1}) and Rosemarie (6.94–3.66 mg g^{-1}). Slice thickness also affected the amount of phenolic content. The amount of this compound significantly decreased with increasing slice thickness. This could be due to thicker slices frying for a longer time. According to the literature, the longer cooking (boiling or frying) time causes greater losses of the total phenolic content [47]. The frying temperature was found to have a significant effect on the amount of total phenolic content of chips. An increased frying temperature decreased the amount of phenolic content and the losses were from 43.17 to 74.19% and from 45.89 to 77.87% for 180 °C and 160 °C, respectively. Recently, Silveira et al. [48] reported that frying at 180 °C reduced the total phenolic content in coloured and light-yellow-fleshed potato chips from 41 to 65%, compared to raw potatoes. From these results, it follows that phenolic compounds are very sensitive to the high temperatures applied during frying process. This is confirmed by research by Kita et al. [49]. These scientists showed that the frying process (170 °C) decreased the total polyphenols content in the purple-fleshed potato chips from 40% (cv. Blue Congo) to 60% (cv. Vitelotte).

Table 3. The influence of cultivar, slice thickness and frying temperature on the total phenolic content, total anthocyanin content and total fat content of the chips produced from coloured potato cultivars.

Potato Cultivar	Slice Thickness (mm)	Frying Temperature (°C)	Total Phenolic Content (mg g^{-1} DM)	Loss of Phenolic (%)	Total Anthocyanins Content (mg g^{-1} DM)	Loss of Anthocyanins (%)	Total Fat Content (g 100 g^{-1} DM)
Blaue Anneliese	1	160	10.86 ^{a}	43.17	1.95 ^{a}	65.79	38.60 ^{cd}
	1	180	10.34 ^{b}	45.89	1.66 ^{b}	70.87	36.49 ^{e}
	2	160	8.86 ^{c}	53.64	1.91 ^{a}	66.49	39.45 ^{b}
	2	180	6.98 ^{e}	63.47	1.62 ^{b}	71.58	40.52 ^{a}
Valfi	1	160	7.46 ^{d}	57.13	0.72 ^{fg}	73.72	39.54 ^{b}
	1	180	4.77 ^{f}	72.59	0.50 ^{gh}	81.75	35.84 ^{e}
	2	160	4.59 ^{f}	73.62	0.70 ^{g}	74.45	39.25 ^{bc}
	2	180	3.85 ^{g}	77.87	0.44 ^{h}	83.94	37.74 ^{d}
Rosemarie	1	160	6.94 ^{e}	51.06	1.14 ^{c}	57.14	39.50 ^{b}
	1	180	3.81 ^{g}	73.13	0.89 ^{e}	66.54	38.26 ^{cd}
	2	160	3.66 ^{g}	74.19	1.09 ^{d}	59.02	39.05 ^{bc}
	2	180	3.68 ^{g}	74.05	0.84 ^{ef}	68.42	39.04 ^{bc}
p-value	Cultivars		<0.0001		<0.0001		0.0080
	Slice thickness		<0.0001		0.083		<0.0001
	Frying temperature		<0.0001		<0.0001		<0.0001

Cultivars-slice thickness	0.0014	0.2216	0.0008
Cultivars-frying temperature	0.0650	0.3590	0.0009
Slice thickness-frying temperature	<0.0001	0.7761	<0.0001
Cultivars-slice thickness-frying temperature	<0.0001	0.2802	0.2123

Different letters in the same line represent significant differences among averages at p <0.05. DM: dry matter.

A three-way ANOVA showed that only potato cultivar differences and frying temperature significantly influenced the total anthocyanin content (Table 3). The highest amount of this pigment was found in chips of cv. Blaue Anneliese (1.62–1.95 mg 100 g^{-1}), followed by cv. Rosemarie (0.84–1.14 mg g^{-1}) and cv. Valfi (0.44–0.72 mg g^{-1}). In addition, the frying process reduced the total anthocyanin content in chips from 57.14 to 83.94%, compared to raw potatoes. An increased frying temperature significantly decreased these compounds in chips of all tested potato cultivars. In cv. Blaue Anneliese chips, the total anthocyanin content was from 65.79 to 71.58% lower, in cv. Valfi it was from 73.72 to 83.84% lower and in cv. Rosemarie it was from 57.14 to 68.42% lower than in raw potatoes. Those differences among potato cultivars can be related with different compositions of anthocyanins in tubers. According to the literature, malvidin and pelergonidin derivatives were more stable during frying than petunidin derivatives [49]. Research on coloured-flesh potatoes by Jarienė et al. [50] showed that the predominant anthocyanin in potato tubers with dark purple flesh was malvidin, followed by petunidin. In potato tubers with light purple flesh, petunidin was predominant, and in potato tubers with red flesh, pelargonidin was predominant. Other researchers also confirmed that for Valfi, a high content of petunidin (87.2% of total anthocyanin content) is characteristic [51]. Therefore, it can be concluded that the cultivar and high temperature of frying were the major reasons for the degradation of anthocyanins during the preparation in potato chips. An earlier investigation conducted by Kita et al. [49] showed that the frying process (170 °C) induced anthocyanin degradation (38–70%). These authors found that in the purple-fleshed potato cultivars, frying caused bigger losses of anthocyanin content than in red potato cultivars. Brown et al. [52] also determined that purple-fleshed potato anthocyanins are more sensitive during frying. However, there is a lack information about effect of slice thickness and frying temperature on the amount of total phenolic content and anthocyanins of red- and purple-fleshed potato chips.

A statistical analysis demonstrated that the total fat content of potato chips was not significantly influenced by the three-way interactions, while two-way interactions had a significant influence on it (Table 3). The amount of total fat ranged from 35.84 to 39.54 g 100 g^{-1} for thinner (1 mm) chips and from 39.04 to 40.52 g 100 g^{-1} for thicker (2 mm) chips; it was higher for thicker potato chips. Krokida et al. [53] established that the amount of total fat is reduced for increasing frying times, especially for the thinner potato products. By contrast, Abong et al. [22] found that the amount of fat absorbed increased with decrease in slice thickness. The reasons for a discrepancy could be in different parameters of technological processing of the chips, as well as the different cultivars used for their preparation. Frying temperature also significantly influenced the total fat content. The fat content was higher at 160 °C than at 180 °C (Table 3). These results are in agreement with data by other researchers. Yadav et al. [54] evaluated the effects of three different frying temperatures (170, 180 and 190 °C) on the fat uptake characteristics of potato chips. These authors reported that the fat uptake decreases due to the increase in frying temperature.

In studies on traditional potato chips, Moyano and Pedreschi [55] and Abong et al. [22] also found that higher frying temperatures caused lower fat absorption by chips.

3.3. The Physical Characteristics of Coloured-Flesh Potato Chips

The most important quality and acceptability parameters in processing of potato chips are colour and texture. The CIE L* a* b* colour system was applied to estimate the colour of potato chips. The lightness (L*) values were significantly affected by cultivar, the cultivars-slice thickness interaction and the slice thickness-frying temperatures interaction (Table 4). The highest L* values were found for 1 and 2 mm chips of cv. Rosemarie fried at 180 °C (44.06 and 48.09, respectively), while the lowest L* values were found for 1 mm chips of cv. Blaue Anneliese fried at 180 °C (22.47).

Table 4. The influence of cultivar, slice thickness and frying temperature on the colour characteristics and hardness of the chips produced from coloured potato cultivars.

Potato Cultivar	Slice Thickness	Frying Temperature	Colour			Hardness (N)
			L*	a*	b*	
Blaue Anneliese	1 mm	160 °C	33.16 [c]	3.57 [def]	−5.76 [ef]	4.91 [c]
	1 mm	180 °C	22.47 [d]	4.74 [cde]	−6.94 [f]	4.99 [c]
	2 mm	160 °C	29.15 [c]	4.07 [cde]	−3.96 [e]	5.84 [c]
	2 mm	180 °C	32.17 [c]	5.77 [c]	−5.88 [ef]	7.15 [b]
Valfi	1 mm	160 °C	39.48 [b]	2.04 [f]	8.72 [c]	3.91 [d]
	1 mm	180 °C	40.63 [b]	4.76 [cde]	8.27 [c]	2.83 [e]
	2 mm	160 °C	40.42 [b]	2.85 [ef]	12.02 [b]	7.16 [b]
	2 mm	180 °C	43.76 [b]	4.91 [cd]	5.20 [d]	5.60 [c]
Rosemarie	1 mm	160 °C	43.60 [b]	13.33 [ab]	13.46 [b]	3.28 [de]
	1 mm	180 °C	44.06 [ab]	15.01 [a]	13.84 [b]	2.75 [e]
	2 mm	160 °C	40.16 [b]	11.04 [b]	14.12 [b]	8.77 [a]
	2 mm	180 °C	48.09 [a]	11.00 [b]	17.51 [a]	6.94 [b]
p-value	Cultivars		<0.0001	<0.0001	<0.0001	0.0089
	Slice thickness		0.3855	0.0010	0.0482	0.0069
	Frying temperatures		0.0988	0.1029	0.0296	<0.0001
	Cultivars-slice thickness		0.0135	0.2388	0.0032	0.0013
	Cultivars-frying temperatures		0.5588	0.0012	0.2896	<0.0001
	Slice thickness-frying temperatures		0.0016	0.4087	0.1858	0.6200
	Cultivars-slice thickness-frying temperatures		0.0890	0.4628	0.0104	0.0464

Different letters in the same line represent significant differences among averages at $p < 0.05$.

The redness (a*) values in tested potato chips significantly differed with cultivar (Table 4); they were the highest in chips of cv. Rosemarie (11.00–15.01), followed by chips of cv. Blaue Anneliese (3.57–5.77) and cv. Valfi (2.04–4.91). Slice thickness and the cultivars-frying temperatures interaction also affected the redness values of chips. The highest a* values were found for 1 mm chips of cv. Rosemarie fried at 160 °C and 180 °C (13.33 and 15,01, respectively).

A three-way ANOVA showed that potato cultivar, slice thickness, frying temperature and their interaction significantly influenced b* values of chips (Table 4). Chips of cvs. Rosemarie and Valfi indicated that positive values of b* tended towards yellow. However, cv. Blaue Anneliese cultivar produced blue coloured chips (negative b* values). An increased frying temperature increased values of b* in chips of cvs. Blaue Anneliese and Rosemarie, while they decreased in chips of cv. Valfi. When 2 mm chips of cv. Rosemarie were fried at 180 °C, they, significantly, showed the highest value of b* (17.51). A strong negative correlation was determined between the colour coordinates L* and b* and amounts of total phenolic content (r = −0.817, r = −0.809, $p < 0.05$, respectively) and total anthocyanins (r =

−0.772, r = −0.747, $p < 0.05$, respectively). This suggests that with increasing total phenolic content and anthocyanins the colour coordinates L* and b* values are decreasing.

Based on the results of the colour parameters, it can be concluded that chips of cvs. Blaue Anneliese and Rosemarie showed typical colour of raw material. This can be explained to lower the reducing sugar content showed by these cultivars. By the way, chips produced from these cultivars had lower losses of anthocyanins during the frying process. On the other hand, the predominant anthocyanin in cv. Valfi is petunidin [51], which is very sensitive to higher temperatures [49]. The higher amount of reducing sugars induces a browning of the processed potato chips during frying [44]. According to the literature, the colour of chips could be influenced by the Maillard reaction, which depends on the amount of reducing sugars and amino acids at the potato tubers, as well as frying temperature and time [21]. Research on coloured potato chips by Kita et al. [7] demonstrated that the values of L*, a*, and b* in purple potato chips ranged from 26.87 to 28.99, 2.15 to 6.61 and −2.62 to 4.42, respectively, while in red chips it ranged from 34.23 to 39.25, 7.41 to 9.82 and 1.48 to 7.25, respectively. These authors also performed the sensory assessment of red and purple-fleshed potato chips. Potato chips with a dark purple colour, which had negative b* values and L* values below 29, gained the highest score (4.58 points from 5 possible points) of overall acceptability. In addition, high quality potato chips were also obtained from cv. Highland Burgundy Red tubers with a dark red flesh colour (4.12 points from 5 possible points).

Potato cultivar, slice thickness, frying temperature and their interaction significantly influenced the hardness of chips (Table 4). A higher frying temperature significantly decreased the hardness of 1 mm and 2 mm thick cv. Valfi chips, as well as 2 mm thick cv. Rosemarie chips, while it increased the hardness of 2 mm thick cv. Blaue Anneliese cv chips. It was found that the texture of chips depended on dry matter content in raw potato tuber. Chips of cvs. Rosemarie and Valfi of 1 mm slice thickness fried at 160 and 180 °C had the least hardness, while, significantly, chips of cv. Blaue Anneliese were the hardest. As can be seen in Table 2, tubers of cv. Blaue Anneliese contained the highest amount of dry matter. Kita et al. [56] evaluated the influence of frying temperatures on the texture of traditional potato chips and reported that the hardness of chips was reduced by increasing frying temperatures. The results of this study showed that hardness significantly increased with an increase in slice thickness (Table 4). These results are consistent with other results reported by Abong et al. [21]. These authors found that the hardness of potato chips significantly reduced with reductions in slice thickness. By contrast, Kaur et al. [19] reported that potato chips fried at 180 °C were harder than chips fried at 120 °C.

3.4. Sensory Evaluation of Coloured-Flesh Potato Chips

The flavour, aroma, colour and texture of potato chips are the most important sensory characteristics on which consumers base their appreciation [37].

A three-way ANOVA showed that potato cultivar differences, frying temperature, slice thickness and their interaction had no influence the flavour of all tested chips (Table 5). The frying temperature was found to have an effect on the aroma of chips. Chips fried at 180 °C had better score for aroma. A statistical analysis demonstrated that the texture of potato chips was significantly influenced by cultivar, frying temperature, two-way interactions (cultivars-slice thickness and slice thickness-frying temperatures) and three-way interactions. The thickness of the slices affected the texture of chips from all investigated cultivars but only when fried at 160 °C. The texture of 2 mm chips of cvs. Blaue Anneliese and Valfi (fried at 160 °C) received the highest rating, while 2 mm chips of cv. Rosemarie received a lower rating.

Table 5. The influence of cultivar, slice thickness and frying temperature on the sensory attributes of chips produced from coloured potato cultivars.

Potato Cultivar	Slice Thickness	Frying Temperature	Flavour	Aroma	Texture	Colour	Total Score
Blaue Anneliese	1 mm	160°C	3.94 [ab]	3.83 [abc]	3.54 [cd]	4.54 [a]	3.96 [abcd]
	1 mm	180°C	4.13 [a]	4.21 [a]	4.54 [ab]	4.61 [a]	4.37 [a]
	2 mm	160°C	4.04 [a]	3.89 [abc]	4.82 [a]	4.54 [a]	4.32 [ab]
	2 mm	180°C	3.93 [ab]	4.04 [abc]	4.54 [ab]	4.34 [ab]	4.21 [abc]
Valfi	1 mm	160°C	3.48 [b]	3.78 [abc]	3.19 [d]	4.36 [ab]	3.71 [d]
	1 mm	180°C	4.06 [a]	3.56 [c]	4.43 [ab]	3.92 [b]	3.99 [abcd]
	2 mm	160°C	3.76 [ab]	3.76 [abc]	3.57 [c]	4.39 [ab]	3.87 [cd]
	2 mm	180°C	3.77 [ab]	3.96 [abc]	3.98 [bc]	3.87 [b]	3.89 [bcd]
Rosemarie	1 mm	160°C	4.03 [a]	3.60 [bc]	4.44 [ab]	4.32 [ab]	4.10 [abc]
	1 mm	180°C	3.92 [ab]	4.00 [abc]	4.45 [ab]	4.13 [b]	4.12 [abc]
	2 mm	160°C	3.53 [b]	3.54 [c]	3.84 [c]	4.54 [a]	3.86 [cd]
	2 mm	180°C	3.90 [ab]	4.09 [ab]	4.44 [ab]	4.43 [ab]	4.21 [abc]
p-value	Cultivars		0.0598	0.1623	0.0020	0.0442	0.0105
	Slice thickness		0.4326	0.6127	0.3449	0.7286	0.7162
	Frying temperatures		0.0565	0.0256	0.0005	0.0514	0.0515
	Cultivars-slice thickness		0.3055	0.5815	0.0093	0.3498	0.6613
	Cultivars-frying temperatures		0.2842	0.1589	0.1473	0.2869	0.9840
	Slice thickness-frying temperatures		0.2970	0.5781	0.0340	0.6840	0.3093
	Cultivars x slice thickness-frying temperatures		0.0537	0.4141	0.0093	0.8013	0.1223

Different letters in the same line represent significant differences among averages at $p < 0.05$.

The colour of potato chips was only significantly influenced by cultivar differences. The mean scores of colour were from 3.87 to 4.61 points (Table 5). Chips of cv. Blaue Anneliese had the highest scores for colour (4.34–4.61 points), followed by Rosemarie (4.13–4.54 points) and Valfi (3.87–4.39 points). According to the literature, food colour is the first quality parameter evaluated by consumers and is critical in the acceptance of the products [21]. Therefore, it is important to select a potato cultivar, such as Blaue Anneliese and Rosemarie, that produces a product with an attractive colour.

The results of the sensory evaluation showed that only potato cultivars significantly influenced the total scores; they were the highest in chips of cv. Blaue Anneliese (3.96–4.37 points), followed by cvs. Rosemarie (3.86–4.21 points) and Valfi (3.71–3.99 points) chips (Table 5). The flavour (4.13 points), odour (4.21 points) and colour (4.61 points) of 1 mm chips of cv. Blaue Anneliese fried at 180 °C received the highest rating.

Abong et al. [21] performed the sensory assessment of potato chips produced from four traditional potato cultivars. These authors found that potato cultivar significantly influenced chip sensory attributes, such as color, flavor, texture and overall acceptability. However, frying temperature and slice thickness did not significantly affect potato chip flavour or texture.

3.5. Principal Component Analysis

A principal component analysis (PCA) was performed to evaluate the relationships between different cultivars, slice thickness, as well frying temperatures, and the seven physico-chemical characteristics presented in Tables 3 and 4. The results of the PCA indicated that 74.72% of the total variance was explained by the first two axes (PC1: 52.82%, PC2: 21.91%) (Figure 1). The eigenvalues of the first principal component (PC1) and second principal component (PC2) were higher than one (3.70 and 1.53, respectively). The colour characteristics L* and b* were highly positively associated with PC1, whereas total phenolic content and total anthocyanins were negatively associated with PC1. The second factor (PC2) was positively associated with total fat content and hardness.

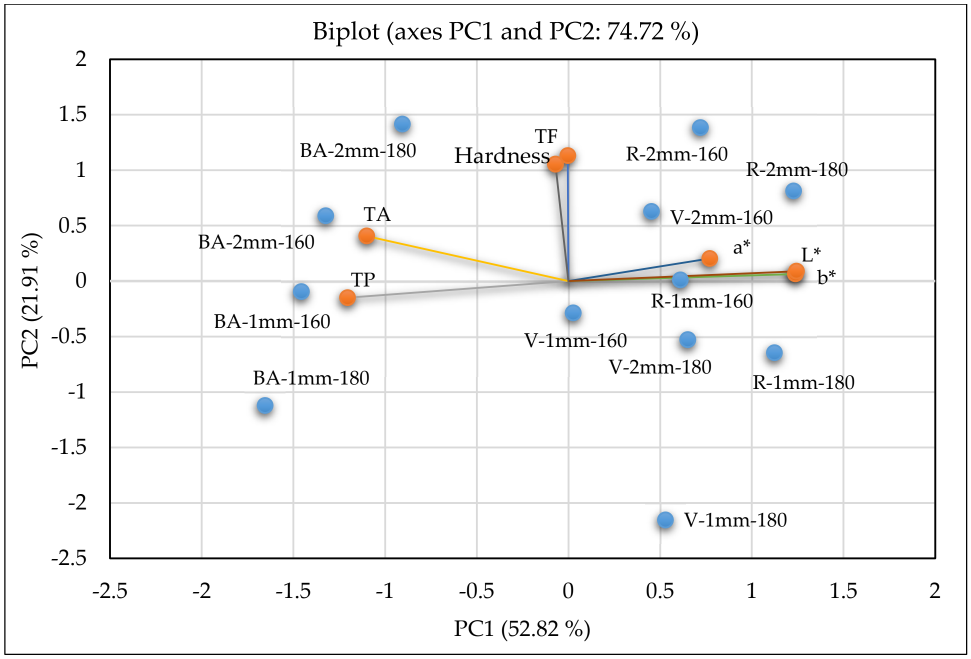

Figure 1. PCA for total phenolic content, total anthocyanins, total fat content, colour characteristics (L*, a* and b*) and hardness of the chips produced from coloured potato cultivars (BA-1mm-160-1 mm chips of Blaue Anneliese fried at 160 °C, BA-1mm-180-1 mm chips of Blaue Anneliese fried at 180 °C, BA-2mm-160-2 mm chips of Blaue Anneliese fried at 160 °C, BA-2mm-180-2 mm chips of Blaue Anneliese fried at 180 °C, V-1mm-160-1 mm chips of Valfi fried at 160 °C, V-1mm-180-1 mm chips of Valfi fried at 180 °C; V-2mm-160-2 mm chips of Valfi fried at 160 °C, V-2mm-180-2 mm chips of Valfi fried at 180 °C, R-1mm-160-1 mm chips of Rosemarie fried at 160 °C, R-1mm-180-1 mm chips of Rosemarie fried at 180 °C, R-2mm-160-2 mm chips of Rosemarie fried at 160 °C, R-2mm-180-2 mm chips of Rosemarie fried at 180 °C).

As shown in Figure 1, the first axis separates the cv. Blaue Anneliese chips from the chips of cvs. Valfi and Rosemarie. All chip samples of Blaue Anneliese (BA-1mm-160, BA-1mm-180 and BA-2mm-160) were grouped closely, due to the higher amounts of total phenolic content and total anthocyanins, as well lower values of colour coordinates L* and b*. The second axis (PC2) mainly separates 2 mm potato chip samples from the 1 mm chips. BA-2mm-180, BA-2mm-160, R-2mm-160, R-2mm-180 and V-2mm-160 were associated with a higher total fat content and hardness.

4. Conclusions

Based on the results of this investigation, it can be concluded that cultivar differences, slice thickness and frying temperature are important factors affecting the physico-chemical and sensory quality characteristics of the chips produced from red- and purple-fleshed potato cultivars. The chips processed from purple-fleshed tubers of cv. Blaue Anneliese showed significantly higher amounts of total phenolic content and total anthocyanins compared to chips produced from the other investigated cultivars. The highest amount of these compounds was found for 1 mm thick slices of chips of cv. Blaue Anneliese fried at 160 °C. An increased frying temperature from 160 to 180 °C significantly decreased the amounts of these compounds. Only chips processed from potatoes cvs. Rosemarie and Blaue Anneliese showed typical colour as raw materials. In addition, the results of the texture analysis established that hardness significantly increased with increasing slice thickness. Chips of cv. Blaue Anneliese received the highest total scores of sensory evaluation. Therefore, potato cv. Blaue Anneliese can be recommended as a raw material for the production of chips. At last, for the production of chips from potatoes with coloured flesh, the slice thickness of 1 mm and the frying temperature of 160 °C are recommended.

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