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Study to Determine the Nutritional Characteristics of Potato Varieties that Are Suitable for the Application of the Freeze-Drying Process

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Abstract

The aim of this study was to determine the nutritional values related to structural stability during the storage of freeze-dried potato cubes and investigate the colour changes that occur during boiling, freeze-drying, and rehydration, as well as the suitability of rehydration and, on the basis of this information, establish varietal characteristics suitable for the use of technology. Nine different potato varieties were analysed. Significant relationships were detected between the amount of dry matter protein and starch content and the colour and colour change values. Significant relationship was measured between the amount of protein calculated in dry matter and the structural stability and rehydration suitability of freeze-dried boiled potatoes. According to our study, the optimal varieties for freeze-dried boiled potatoes were those with high protein content in dry matter, which provided maximum structural stability during storage and optimal properties for short-term rehydration at low temperatures. Based on our study, potato varieties that are suitable for processing by freeze-drying technology can be easily selected and our study provides useful information for breeders, growers, and food processors to achieve their goals in food processing.

Keywords Boiling · Colorimetria · Freeze-dried · Nutrient · Potato variety · Rehydration

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Introduction

The potato (*Solanum tuberosum* L.) is one of the most widely grown crops and a very important part of the human diet (Leo et al. 2008).FAO's data reveals that approximately 375 million tons of potatoes were produced globally in 2022 (FAO DATA 2023). Potatoes play a more significant role in the diets of people in developed countries compared to those in developing countries (Burlingame et al. 2009a). Potatoes exhibit high nutritional value such as high content of carbohydrates, vitamins, pleasant taste and high digestibility. Carbohydrates are the most abundant macronutrient in the given context. Starch dominates the amount of carbohydrates present. Potato starch is composed of amylopectin, a branched chain glucose polymer, and amylose, a straight chain glucose polymer, in a consistent ratio of 3:1 (Woolfe and Poats 1987). The crude protein content of a medium-sized potato is approximately 2–4 g/100 g, depending on the nutritional data used, as well as the variety and preparation methods of the potato (Hoover 2001). Potatoes contain all nine essential amino acids and provide thus "complete" protein (Waglay et al. 2014).

Proteins are compounds that are sensitive to heat. Therefore, thermal treatments used during processing can significantly impact their structure, digestibility and functional properties. The heat treatment does not significantly affect the protein content and amino acid composition but significantly reduces their digestibility (Bailey et al. 2023). Potato proteins can be divided into main categories: patatin (40%), protease inhibitor (50%) and others (10%), where the quantity and ratio to each other can vary greatly depending on the varieties and growing seasons (Bárta et al. 2012). During processing, due to the heat effect, it is basically present in a denatured form, but native patatin has excellent functional properties (Shewry 2003). The water-soluble potato proteins (patatin, protease inhibitors) begin to denature at an average temperature of 55–75 °C, with disruption of the protein structure (Koningsveld 2001).

Recently, the structure and properties of patatin, including its stability and thermal aggregation, have been studied in relation to the production of large functional proteins (Pots et al. 1999a, 1999b). Potato colour can vary depending on the variety, growing conditions and maturity. Certain potato varieties are particularly high in anthocyanins, resulting in a purple, blue or red tint (Fogelman et al. 2019). Association studies were conducted using diploid and tetraploid varieties with different tuber flesh colours to examine the relationship between the expression levels of genes involved in carotenoid biosynthesis and the qualitative and quantitative composition of carotenoids in the tubers (Morris et al. 2004; Sulli et al. 2017; Zhou et al. 2011; Wolters et al. 2010). The major carotenoids found in potatoes are lutein, zeaxanthin and violaxanthin, all of which are xanthophylls (Brown 2005). The quality of food is determined by the sum of these qualities, which should also be conveyed to as well as available for consumers who have access to preserved food only because of their special job or circumstances, e.g., climbers, soldiers or astronauts. Quality is largely determined by the preservation technology and its parameters.

One of the main objectives of food preservation is to maintain quality characteristics while ensuring food safety.

Freeze-drying (FD) is a specific preservation technique. The consumption of potatoes is part of our daily diet, and it is therefore necessary to have available the same size and quality of potatoes as we consume. A special technology for food preservation is FD which has many beneficial properties, such as endowing a long shelf life via removing moisture and inhibiting the growth of bacteria, yeast, and mould, allowing food to remain edible for longer periods of time, often years or even decades (Dincer 2003). It retains the colour, original flavour, most vitamins and minerals, making it a healthier option (Waghmare et al. 2021). It is highly advantageous for weight loss because it removes moisture from products, making it ideal for cost-effective transportation. The sublimation of water results in the creation of a highly porous structure that allows immediate rehydration (Jia et al. 2019). The rehydrated, ready-to-eat food is expected to regain the properties of the original product. Both thermally processed and freeze-dried foods exhibit changes in quality. Three main factors can be characterised concerning food quality. These are physical, nutritional and chemical properties (Ratti 2013). In general, the drying process can affect colour, odour, rehydration properties, flow properties, water activity and the retention of nutrients and volatile compounds (Sablani 2006). FD food is suitable for ready-to-eat applications, such as hiking food or military rations (Meals Ready to Eat, MRE) due to its light weight, very low moisture content and fast-food-amenable character. The publications of freeze-dried potatoes mostly look at puree-like foods in powder form. For freeze-dried foods, rehydration is critical for readiness for consumption. Commercially available freeze-dried ready meals usually require boiling water and 15 min of preparation time. These parameters are difficult to obtain off-site.

This study aimed to determine the characteristics of potato varieties that are suitable for the application of the freeze-drying process.

Materials and Methods

Materials

The samples were obtained from the Potato Research Center of the Hungarian University of Agriculture and Life Sciences, Keszthely, Hungary, and were harvested from the 2023 crop, planted to field (loamy soil) in April first and harvested in August last decade. Standard, generally used potato cultivation techniques were applied without irrigation. Plant nutrition was applied by complex fertiliser in November (N:P:K, 8:16:30, 1 t/ha) and 100 kg/ha NH_4NO_3 (27% N) right before planting. Following harvest, samples were stored in the dark at temperature 8–10 °C, in accordance with standard potato storage conditions. The samples were transported from Keszthely to Debrecen by car in raschel bags and used immediately after their arrival without any delay. Samples originated from six varieties: Arany chipke, Balatoni rózsa, Basa, Démon, Hópehely and Somogyi kifli and three variety candidates: "14.21", Balatoni sárga and Golden river. The varieties are listed in the National, EU and OECD List of Varieties; the variety candidates are still in the process of being released. These varieties were bred in Hungary and account for 10–15% of the potatoes grown in Hungary, but they are nevertheless representative of the known kitchen ethnologically defined types of categories A, B and C. The selection was made on the basis that there should be at least three of each type. These varieties are commercially available. As a result of the breeding, they are generally better able to withstand the more extreme dry weather conditions.

Preparing Samples

The potato samples were peeled and chopped into 1.5 × 1.5 × 0.5-cm cubes. They were then boiled on an induction plate (ZANUSSI ZEI6640XBA, Europe Group Companies, Electrolux Home Products, France) at atmospheric pressure in water until they reached the technologically boiled condition (35–45 min depending on the variety, easy to cut through with a knife, but not overboiled), and subsequently cooled in cold tap water. The samples were placed in a plastic tray and freeze-dried using the institute-owned freeze-drier developed by the University of Debrecen. The temperature of the samples was measured during treatment using a built-in core thermometer. The FD process was completed at a core temperature of 42 °C, with a minimum treatment time of 24 h to ensure complete moisture removal and post-drying operations (Defense Logistics Agency 2023). After the procedure, the products were vacuum-packed immediately at − 1 bar pressure into plastic bags by a MAXIMA MVAC 300 vacuum-packing machine (Maxima Holland Spangenberg International B.V., Mijdrecht, Utrecht, The Netherlands). Each bag contained 30-g freeze-dried boiled potato.

Digital Optical Analysis

A microscope was used to conduct a surface analysis of the potato structure in order to identify any potential fractures or injuries. Photos were taken of the potato in a dry state after the storage test. Microscope examinations were conducted using an Olympus MVX10 macro view with 0.63–4 × magnification (OLYMPUS Corporation, Japan) and the SZX2-ILLK Transmitted Light Illumination system (OLYMPUS Corporation, Japan) connected to CellSens Entry 1.18 software (OLYMPUS Corporation, Japan). Image analysis on the recordings was performed using the ImageJ 1.54f java 1.8.0_322 (64-bit) software. The 2D area of the optically visible surface of the crystallised starch grains, measured, made 10 measurements and calculated a mathematical average from the results.

Structural Stability Analysis Method

The freeze-dried potato samples were stored in a vacuum pack at room temperature (22 °C) in the dark (to prevent oxidation, colour change and degradation of flavours caused by light) for 45 days. The vacuum bags (five per variety/variety candidates) were opened. The fragmented parts and the unfragmented parts were then separated and fractionated. They were sifted through a sieve with a hole diameter of 1 mm and split into two fractions: for fractions of 1.0–10 mm and less than 1.0 mm. The masses of the fractions were measured with a scale (ADVENTURER PRO AV4102C, Ohaus Corporation, Switzerland), and the percentages of the masses were calculated.

Colorimetric Analysis Method

Colour measurement was performed with KONICA MINOLTA CR-410 (KONICA MINOLTA SENSING, INC. JAPAN) handheld apparatus measuring L^* a^* b^* values approved by the Comision Internationale de l' Eclairage (C I E):

$$\Delta \mathrm{E} = \sqrt{\Delta a^{*2} + \Delta b^{*2} + \Delta L^{*2}} \tag{1}$$

where L^* is the perceptible light,

a^*: colour coordinate from red ($+a^*$) to green ($-a^*$)

b^*: colour coordinate from yellow ($+b^*$) to blue ($-b^*$)

The measurements were taken under instrumental conditions with a 5-cm diameter aperture at room temperature. The colour of raw potatoes, boiled potatoes (before FD), freeze-dried and following rehydration was measured five times to obtain an average value for statistical analysis. The coefficient of variation (CV) value was calculated before accepting the data. The CV value was less than 10, except for one series of measurements which had a value of 11.2. A CV value lower than 10 indicates homogeneity of the data and acceptance of the results.

Rehydration Suitability and Palatability Test

The changes in different potato varieties during rehydration at low temperatures were observed by subjecting freeze-dried products to rehydration. The rehydration water temperature was set at 30, 40 and 50 °C, and the rehydration time was 10 min. The rehydration times were designated according to the requirements of the United States Defense Logistics Agency, The Nation's Combat Logistics Support Agency, which sets the preparation time for dehydrated foods for soldiers between 5 and 12 min (Répás et al. 2023). Instrumental measurements were not used because the results became extremely diverse. Optical observation was carried out, and it was examined whether the structure disintegrated and did not fall apart under the influence of rehydrating water.

Palatability test was carried out on potato samples rehydrated at different temperatures involving five people. During the study, only the sensation in the mouth had to be taken into account, how similar the texture of the product was to the consistency of the original boiled potatoes. A point system ranging from 0 to 10 was used for the assessment. The least similar was denoted by 0 points, and the most similar was denoted by 10 points. Taste occurred during rehydration at 2, 4, 6, 8 and 10 min.

Analytical Methods

The National Accreditation Body of the Hungary (member of the European Accreditation organisation) accredited Central Laboratory of Agricultural and

Food Products at the Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen, conducted the analyses. The sample was homogenised using a blender. Analytical analysis was performed immediately after the shredding process to minimise exposure to external conditions. All results were determined based on the dry matter content.

Dry Weight

The dry matter content of samples was determined by measuring the residue obtained after the products were dried to a constant weight at 103 °C per 100 g. A 10-g homogenised sample was dried, with the mass obtained after drying representing the dry matter. The weighing vessel was dried at 103 °C, cooled in a desiccator and weighed on an analytical balance. The process was repeated three times, resulting in a standard deviation below ± 0.4 m/m%.

Protein

Protein content was determined as total nitrogen content by Kjeldahl method (ISO 5983–2:2009) and using the coefficient 6.25 for calculation. All chemicals used were from VWR International Ltd. (Geldenaaksebaan, Belgium).

Starch

Starch content was determined by polarimetry method by Hungarian Standard Body 6830–18:1988 which differs as follows from ISO 10520 7.1. point: 25 g of a properly homogenised sample was weighed to the nearest 1 mg in a 100-ml polarizing flask. Next, 25 ml of 0.3 M hydrochloric acid solution (VWR, Belgium, Geldenaaksebaan) was added, and the flask was shaken several times while it was boiled for exactly 15 min in a water bath. Once removed from the water bath, the flask was cooled, and 5 ml of Carrez I (VWR, France, Les Aires) solution was added, followed by 5 ml of Carrez II (VWR, France, Les Aires) solution. The mixture was filled with deionised water and filtered through pleated filter paper (150 mm, 87 g/m^2), ensuring that the solution was clear and reflective. If the solution was not reflective, the process was repeated using a larger amount of Carrez solutions. Finally, the optical rotation of the filtrate was measured with a polarimeter (α). The ethanol originated from VWR, France, Fortanay-sous-Bois.

Starch content was calculated by the following formula:

$$K = \left(100 - \frac{100 * (\alpha - \alpha\prime)}{\alpha^{D20} * l * m}\right) \times f \tag{2}$$

where

α: total optical rotation, degrees

α': optical rotation of alcohol-soluble components at 40% vol, degrees

α^{D20}: specific rotation (185.5 for potatoes)

l: length of polarimeter, dm

m: mass of sample weighed for analysis, g

f: conversion factor from the wavelength of measurement to the D-line of Na (589 nm)

Reducing Sugar

The reducing sugar content was determined according to the Hungarian Standards MSZ 6830–26:1987, using the Luff-Schoorl method. The Carrez I, II originate from VWR, France, Les Aires; the ethanol originated from VWR, France, Fortanay-sous-Bois; and the sulphuric acid and thiosulfate originated from VWR, Belgium, Geldenaaksebaan.

Statistical Analysis

Statistical analyses were performed using R Studio (2R Core Team 2022). The nutrient values of the potato samples were compared with the percentages of whole, unfragmented fractions, and the colour measurement data were also compared with the nutrient values of the potato samples' dry matter content and correlation calculation was performed. The results obtained were evaluated according to Guilford (Guilford 1950). Only values higher than 0.4 were considered, which is lower than the limit and already indicated a medium correlation and a significant relationship, and values lower than this were not evaluated.

Principal component analysis was performed on the results by XLSTAT Trial statistical Microsoft Excel software which is equivalent to the full version of the program (Lumivero 2024).

Results

Digital Optical Analysis

Microscopic photos of the considered varieties after freeze-drying potatoes are shown in Fig. 1.

The surface exhibits a granular structure while also displaying unique characteristics. The figure includes detailed images of both poorly performing and excellent performing varieties after FD. The results of the measurements are shown in Table 1.

The size of the starch grain of freeze-dried boiled potato samples was compared with the nutritional content of potatoes by correlation analysis method. The results (*r*) are presented in Table 2.

The *r* values between the size and protein and starch contents of the grains of freeze-dried potatoes were − 0.573 and − 0.628, which indicates a statistically median correlation, indicating a significant relationship (Fig. 2).

The size of the starch is 10–110 µm, with an average of 40–50 µm (Chung et al. 2014). The physicochemical properties and functional performance of

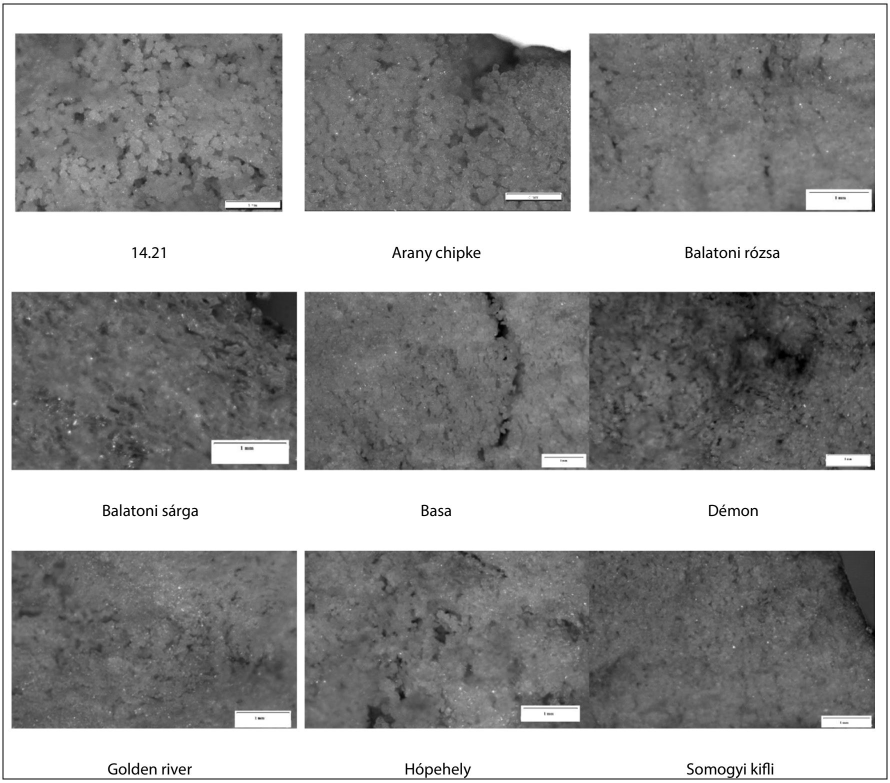

Fig. 1 Microscopical photos of freeze-dried boiled potato of different varieties

Table 1 2D surface of the freeze-dried boiled potato starch

Varieties/variety candidates	Area (μm^2)
Somogyi kifli	1737.04
Démon	2729.72
14.21	8174.22
Balaton rózsa	5194.15
Arany chipke	9407.26
Basa	11,938.24
Hópehely	17,032.35
Golden river	20,896.01
Balatoni sárga	26,635.21

starch are influenced by several factors, including the structural structure of amylose and amylopectin in starch grains (Vamadevan and Bertoft 2015). This depends on the variety of potato, maturity and growing conditions (Copeland et al. 2009). The chemical composition and structure of starch grains vary

Table 2 Correlation between starch size and nutrient content in freeze-dried boiled potatoes ($p = 0.05$)

Matter	Area
Dry matter (g/100 g)	– 0.895
Protein (g/100 g)	– 0.573
Starch (g/100 g)	– 0.628
Reducing sugar (g/100 g)	0.629
Protein to dry matter (g/100 g)	– 0.024
Starch to dry matter (g/100 g)	0.171
Reducing sugar to dry matter (g/100 g)	0.712

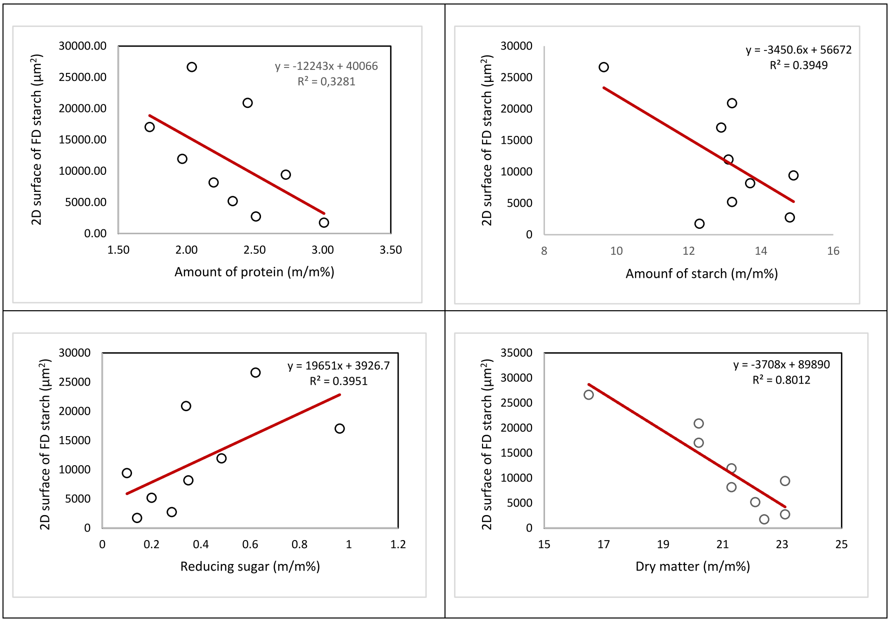

Fig. 2 The relationship between starch size, nutrients and dry matter content in boiled freeze-dried potatoes

significantly with grain size. (Cai et al. 2014). According to grain size, small grains have lower amylose content, higher lipid, protein and mineral content and smaller crystal structure than large grains (Dhital et al. 2011).

It also depends on spatial location because the amylose molecule is concentrated on the periphery of larger starch grains (Pan and Jane 2000; Chen et al. 2019). Differences in composition, structure and size of starch grains affect their functional properties in food, including swelling, gelatinisation, retrogradation, flowability, digestibility, baking properties and their susceptibility to chemical modification (Li et al. 2023).

Structure Stability Analysis

The results of the nutrient content and results of the calculated dry matter amount are shown in Table 3.

The values obtained corresponded to those in the various variety descriptions, so they were accepted (Burlingame et al. 2009b).

The image and the results of the structural stability of different type of freeze-dried potato are shown in Fig. 3 and Table 4.

The correlation between the data was − 0.3723. The multiple *R*-squared correlation value was 0.0140 (p-value: 0.05), indicating no significant relationship between the variables (Fig. 4).

Figure 5 shows the relationship between the amount of reducing sugar calculated per dry matter and the results obtained during the structure stability test.

There was no significant correlation between the data, as indicated by the correlation coefficient of − 0.0602 and the multiple *R*-squared correlation value of 0.0036 (p-value: 0.05).

Figure 6 shows the relationship between the amount of protein calculated per dry matter and the results obtained during the structure stability test.

The correlation between the variables was found to be high, with a coefficient of 0.8276. The multiple *R*-squared correlation value was 0.685 (p-value = 0.05). Linear relationship between the variables could be detected.

Equation of straight line (mean) $y = 12.065x + 68.029$.

Upon examining the ratio of fragmented fractions in relation to nutrient content, no significant correlation was found with the amount of calculated reducing sugars in the dry matter. The correlation with the quantity of fraction 1–10 mm was weak (− 0.1614). For fractions smaller than 1.0 mm, there was no relationship (0.1885). Upon examination of the ratio of fragmented fractions in relation to nutrient content, no correlation was found with the amount of calculated starch in the dry matter. A weak correlation of 0.2167 was observed with the quantity of fraction 1–10 mm. For fractions smaller than 1.0 mm, the correlation was 0.1250, indicating no

Table 3 Nutrient content of potatoes (g/100 g)

Varieties	Dry matter	Protein	Starch	Reducing sugar	Protein to dry matter	Starch to dry matter	Reducing sugar to dry matter
14.21	21.3	2.20	13.7	0.349	10.33	64.32	1.64
Arany chipke	23.1	2.73	14.9	0.100	11.82	64.50	0.43
Balatoni rózsa	22.1	2.34	13.2	0.200	10.59	59.73	0.90
Balatoni sárga	16.5	2.04	9.7	0.622	12.36	58.48	3.77
Basa	21.3	1.97	13.1	0.484	9.25	61.50	2.27
Démon	23.1	2.51	14.8	0.282	10.87	64.07	1.22
Golden river	20.2	2.45	13.2	0.340	12.13	65.35	1.68
Hópehely	20.2	1.73	12.9	0.963	8.56	63.86	4.77
Somogyi kifli	22.4	3.01	12.3	0.141	13.44	54.91	0.63

Fig. 3 Results of structure test of freeze-dried potatoes (Balatoni rózsa)

Table 4 Results of the structural stability of different type of freeze-dried potato

Varieties	Mean of unbroken parts (%)	Std. deviation of unbroken parts	Fragmented parts (%)	Parts of 1–10 mm (%)	Parts of < 1 mm (%)
Basa	37.0	0.78	63.0	34.4	28.6
Balatoni rózsa	40.5	1.01	59.5	26.4	33.0
Hópehely	50.0	2.32	50.0	30.0	20.0
Démon	53.5	0.58	46.5	24.6	21.9
Arany chipke	59.3	0.93	40.7	30.1	10.6
14.21	68.4	0.18	31.6	10.5	21.1
Golden river	88.7	3.42	11.3	7.9	3.3
Balatoni sárga	89.7	2.40	10.3	7.9	2.4
Somogyi kifli	99.0	0.55	1.0	0.0	1.0

relationship. Upon examining the ratio of fragmented fractions in relation to nutrient content, a correlation was found with the amount of calculated protein in the dry matter. Specifically, there was a correlation of – 0.5057 with the quantity of fraction 1–10 mm, and a correlation of 0.5487 with fractions smaller than 1.0 mm, indicating a medium correlation and a significant relationship. Additionally, there was a correlation of – 0.7324 between broken parts and the amount of protein calculated as dry matter. During colour measurement, a correlation analysis was performed on the

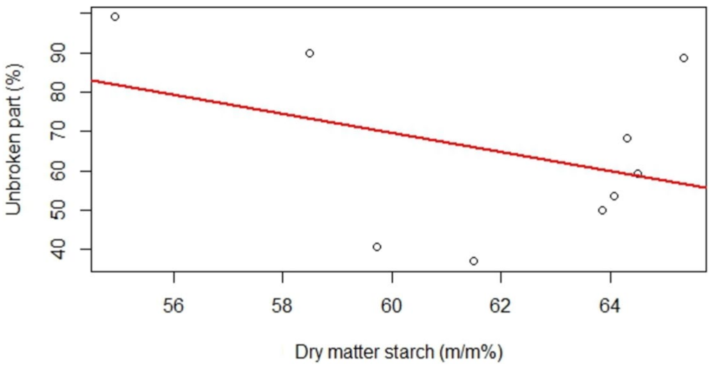

Fig. 4 Relationship between the amount of dry weight starch and the stability structure test

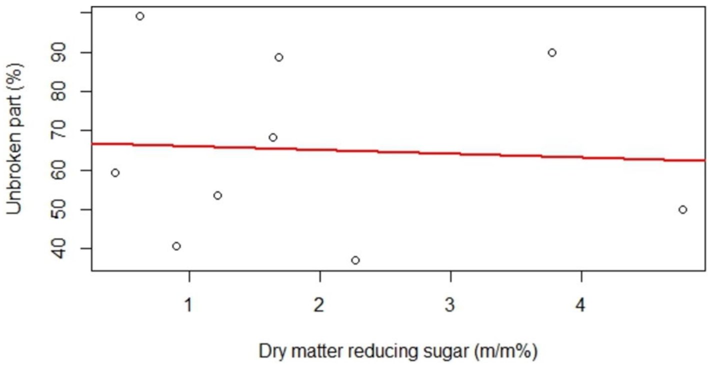

Fig. 5 Relationship between the amount of dry matter reducing sugar and the structure stability test

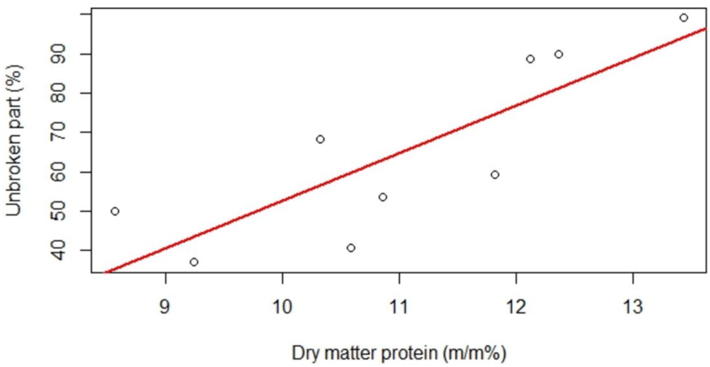

Fig. 6 Relationship between the amount of dry weight protein and the structure stability test

Table 5 Result of the correlation analysis between colorimetric and potato dry weight nutritional values

	Value	Unbroken parts (%)	Protein to dry matter	Starch to dry matter	Reducing sugar to dry matter
Raw potato	L*	-0.6112	-0.6055	0.3409	0.2191
	a*	0.0886	0.2884	-0.7196	0.2732
	b*	0.4887	0.6116	-0.3184	-0.1856
Boiled potato	L*	0.5812	0.4925	-0.3703	-0.4279
	a*	0.3265	-0.0596	0.1217	0.0553
	b*	0.3794	0.6878	-0.3778	-0.4471
Freeze-dried boiled potato	L*	-0.3843	0.4897	0.5770	0.2631
	a*	0.0123	0.0270	0.0859	0.0940
	b*	0.2959	0.2825	-0.2838	0.1018
Rehydrated freeze-dried boiled potato	L*	-0.4883	-0.5337	0.6079	0.2776
	a*	0.0981	0.2718	-0.0198	0.4947
	b*	0.2126	0.4514	-0.3875	-0.2014
Raw / boiled potato	ΔL*	0.7013	-0.7168	0.3693	0.5789
	Δa*	-0.0606	0.2617	-0.7464	-0.2177
	Δb*	-0.1169	-0.2949	0.6076	0.2942
	ΔE	0.1519	-0.0327	0.1125	0.1746
Boiled / rehydrated potato	ΔL*	-0.4653	-0.5268	0.5796	0.5096
	Δa*	-0.2065	-0.3275	-0.1164	0.5288
	Δb*	0.3858	-0.4786	0.0505	0.3210
	ΔE	0.0294	-0.0403	0.2184	0.2362

medium correlation, significant relationship

high correlation, marked relationship

results. The nutrient value in dry matter was calculated and compared using quantities. The results are displayed in Table 5.

Colourimetric Analysis

The correlation between the amount of reducing sugars in dry matter and the colour measurements was slight. Specifically, the correlation with the *L** value of boiled potatoes was – 0.4279, and with the *b** value, it was – 0.4471. After rehydration, the correlation with *a** was 0.4947. Upon examining the differences, the correlation of the magnitude of the change in brightness (Δ*L**) between raw and boiled potatoes was 0.5789. Therefore, the increase in reducing sugar in raw potatoes resulted in a corresponding increase in the brightness of the boiled product, as observed in boiled and rehydrated potatoes. The correlation coefficient was 0.5096, indicating a moderate positive correlation between the amount of reducing sugars and the change in Δa^*. Additionally, the magnitude of the change in Δa^* was positively correlated with a coefficient of 0.5288. The correlation between the amount of starch in dry matter and the a^* value of raw potatoes was strong (−0.7196), indicating a significant relationship. Additionally, the L^* value of freeze-dried potatoes exhibited a correlation coefficient of 0.5770, which persisted even after rehydration (0.6079). The correlation was also observed with various magnitudes of change in the measured colour values. The correlation between raw and boiled potatoes was strongest for the colour parameters Δa^* and Δb^*, with correlation coefficients of −0.7464 and 0.6076, respectively. Additionally, there was a moderate correlation between the lightness parameter ΔL^* of boiled and rehydrated potatoes, with a correlation coefficient of 0.5796. The amount of protein in dry matter showed a moderate negative correlation with the lightness parameter L^* of raw potatoes ($r = -0.6055$, $b^* = 0.6116$). However, this correlation decreased after rehydration, with a correlation coefficient of 0.4514 and a decrease in L^* value of −0.5337. A significant correlation was observed between protein content and colour in potatoes, as evidenced by the correlation coefficient of 0.6878 in boiled potatoes. The correlation between protein content and the change in L^* value between raw and boiled stock was −0.7168. The correlation was −0.5268 between L^* values in the boiled and rehydrated states. Correlation analysis was also performed between the examined results of structural stability and the results of light metering. The correlation between the uncrushed parts and the raw value L^* is −0.6112, and the correlation between the boiled value is 0.5812. The correlation between the luminance change between raw and boiled potatoes and the parts remaining whole in the structural study was 0.7013.

Rehydration Suitability and Palatability Test

Photos of the rehydration trials are shown in Fig. 7.

Microscopic images clearly show small and large cracks formed during rehydration. On the basis of this image, a stable structure can be inferred in the case of "Arany chipke," "Balatoni sárga," "Golden river" and "Somogyi kifli." In the case of Balatoni rózsa and "Basa", the pictures clearly show the complete disintegration of the structure along the large and strong cracks.

During the sensory examination, only the sensation in the mouth was observed, and how similar the consistency was to the consistency of the original boiled potato. The results are shown in Tables 6, 7 and 8.

Balatoni rózsa received the lowest ratings, and potatoes with lower protein content, calculated on dry matter basis, received lower ratings. It disintegrated easily and almost disintegrated during rehydration. Several varieties received medium ratings, but the highest ratings were given to the varieties Balatoni sárga and Somogy kifli. Both varieties had high protein content in dry matter.

Fig. 7 Photos of rehydrated different variety freeze-dried boiled potato

Table 6 Results of palatability test at 30 °C

Varieties	Texture point (0–10)				
	2′	4′	6′	8′	10′
14.21	3	5	4	4	4
Arany chipke	5	5	6	6	7
Balatoni rózsa	8	7	4	2	2
Balatoni sárga	6	6	7	8	8
Basa	5	5	6	6	7
Démon	4	4	4	3	3
Golden river	5	5	5	4	4
Hópehely	3	3	4	5	4
Somogyi kifli	6	7	7	8	8

Table 7 Results of palatability test at 40 °C

Varieties	Texture point (0–10)				
	2′	4′	6′	8′	10′
14.21	3	5	4	4	5
Arany chipke	5	5	6	7	7
Balatoni rózsa	5	5	4	2	1
Balatoni sárga	6	6	7	8	8
Basa	5	6	6	7	7
Démon	4	5	4	4	5
Golden river	4	4	5	4	5
Hópehely	3	4	4	5	5
Somogyi kifli	7	8	8	8	9

Table 8 Results of palatability test at 50 °C

Varieties	Texture point (0–10)				
	2′	4′	6′	8′	10′
14.21	3	5	4	4	5
Arany chipke	5	6	7	7	7
Balatoni rózsa	7	6	4	3	1
Balatoni sárga	6	6	7	8	9
Basa	5	6	6	7	7
Démon	4	5	4	4	4
Golden river	4	5	5	4	4
Hópehely	3	3	4	5	5
Somogyi kifli	8	8	9	9	9

Principal Component Analysis

We performed a principal component analysis on the nutrient content of potatoes, colour measurements made at different stages and structural stability test results. Results are shown in Figs. 8 and 9.

According to the scree plot diagram (Fig. 8), it was enough to use three active variables to determine the results of active observation, because in F3 axis, the cumulative variability reached 90%, and in case of using 4 variables, the cumulative variability was more than 95%. In this case, it was enough to measure the raw matter nutritional quality and two measurements from the colour analysis.

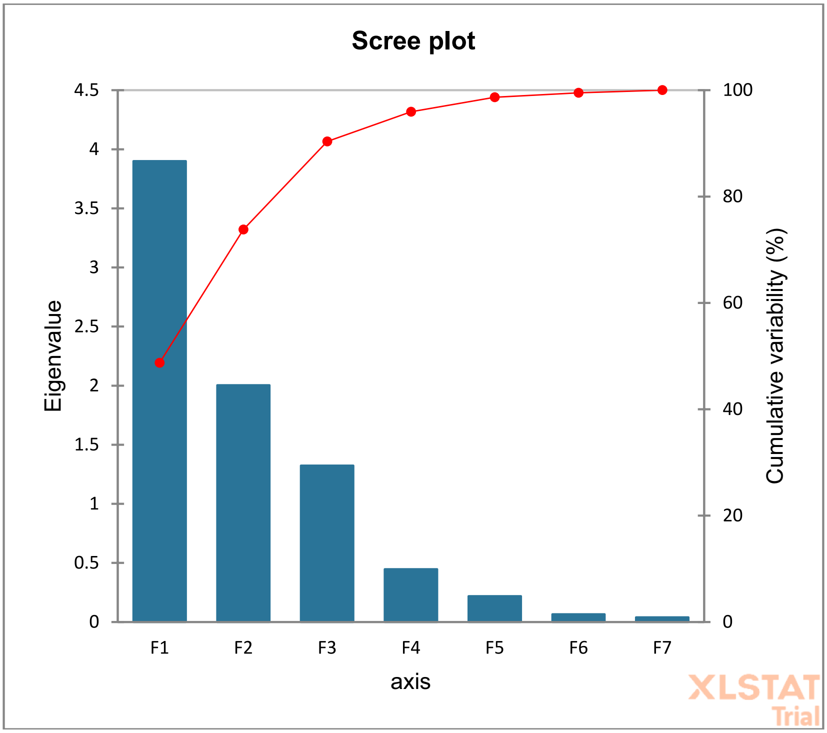

Fig. 8 Scree plot diagram of the variables (plot of the eigenvalues of factors)

Discussion

Limited research has been conducted on the characteristics of freeze-dried boiled potatoes. The measurements indicate that the presence of protein significantly contributes to the structural stability of potatoes, while starch and reducing sugars have minimal influence. Potato texture is a complex property that depends on various factors, such as dry matter content, specific gravity, amylose and sugar levels, as well as protein and nitrogen levels in the tubers (Arvanitoyannis et al. 2008; Jitsuyama et al. 2009). The texture is also determined by the size and structure of starch grains in raw tuber tissue (Thybo et al. 2006). There is also a difference in the structure of the starch particles (Faulks and Griffiths 1983). During the cooking process, the starch in potatoes undergoes gelatinisation, which creates pressure in the cells as it expands. The texture of the potato is determined by the amount of gelatinised starch in the cells. Floury potatoes have a dry and granular texture, while waxy potatoes have a wet and rubbery texture. Cells with more gelatinised starch have a floury consistency, while those with less starch and more water have a waxy consistency (Martens and Thybo 2000). In the waxy cell type, water that is loosely retained is released when chewed after cooking, creating a moist mouth sensation. On the other hand, gelatinised starch of the floury type retains water, resulting in a sensation of dryness in the mouth. This

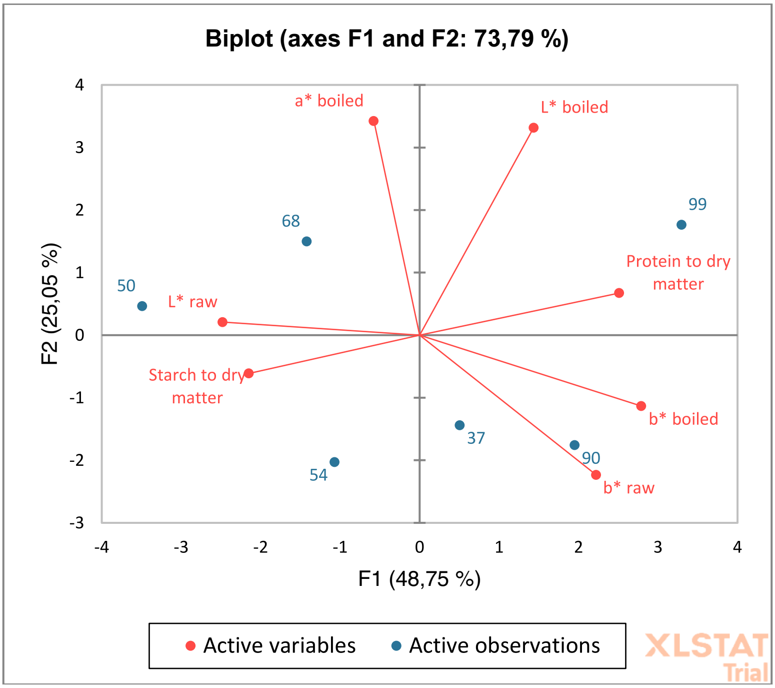

Fig. 9 Biplot diagram of the variables (Active variables: results of the nutritional analysis and results of the colour analysis; active observations: results of the structure stability test—unbroken parts)

is an important quality feature that is related to the recommended use of kitchen technology (Smith et al. 2009). The process will cause changes in functional properties due to irreversible changes in the structure of starch granules and loss of crystal structure. Additionally, the chiralised starch will retrograde to form RS2-type–resistant starch. FD weakened the crystal structure of potato starch granules and formed pores, while normal drying and ethanol drying had no significant effect on the crystal structure (Bao et al. 2021). In contrast, based on the results of Buzera et al., FD had no significant effect on the structure or crystal skeleton of starch grains. Similar results were presented by Qiu et al. (Buzera et al. 2022; Qiu et al. 2019). Bao et al. (2021) reported a structural change in the thermal parameters of potato flours resulting from FD. The freeze-dried flours had significantly lower thermal transition temperatures compared to the other two physical treatments due to damage to the starch crystals during drying. Additionally, the freeze-dried potato flour had a much higher viscosity, which was also associated with structural changes in the grain surface. Guedes et al. (2021) investigated the effect of drying supplemented with ethanol treatment on the technological properties of potatoes. The combined treatment reduced the drying time by approximately 60%, while the initial rehydration time increased by 25%. The effect was mainly due to changes in the potato cell wall. The effect on starch granules, including granule shape, surface area and structure, was not significant (Guedes et al. 2021). The water absorption of freeze-dried potato flours is greater due to the disruption of starch granules. In contrast, conventional oven drying results in a more ordered structure of the starch amorphous regions, resulting in lower viscosity (Hormdok and Noomhorm 2007). Cell wall characteristics can also affect texture (Jarvis and Duncan 1992; Jarvis et al. 1992). The activity of pectin methylesterase is crucial for the formation of firm tissue during cooking by crosslinking pectin in the middle lamella (Pan and Jane 2000). The various varieties differ in their cell wall density and the extent to which the median lamella and cell wall dissolve, which ultimately affects the texture (Van Marle et al. 1997). When comparing the results of the structural stability study, microscopic images reveal that weaker performing varieties such as Balatoni rózsa, Basa and "Hópehely" have a fragmented, deeply open, large-grained, floury-like structure. In contrast, well-performing varieties like Balatoni sárga and "Somogyi kifli" have a coherent, small-grain-size, crack-free, waxy structure. The distance between particles was not significantly different among the studied varieties, based on the microscopic images in Fig. 1. These findings are consistent with the results reported by Martens and Thybo (Faulks and Griffiths 1983). The water-binding capacity of potato proteins is crucial in the production of protein coagulates. Various drying methods, such as drum drying, spray drying and freeze drying, have significantly enhanced this ability. Freeze drying, in particular, has yielded exceptional outcomes depending on the pH (Knorr 1982). When dealing with dried products, the rehydration rate is a crucial parameter. This refers to the speed and extent to which the material can be rehydrated to its original moisture content. Tüfekci et al. discovered a correlation between the drying temperature and the rehydration rate. The rehydration rate of sweet potatoes dried at different temperatures and by different methods (microwave, conventional) was studied. It was found that above a certain temperature, the rehydration rate decreased due to rapid and drastic shrinkage of the plant tissue, which prevented rehydration (Tüfekçi and Özkal 2023). Potato colour depends on the amount of carotenoids present. Isocitrate dehydrogenase (IDH) is an enzyme that plays a crucial role in the carotenoid synthesis pathway by mediating the formation of alpha-ketoglutarate. The activity of IDH is affected by the dry matter and protein content, which in turn affects the levels of alpha-ketoglutarate and the biosynthesis of carotenoids (O'Carra and Mulcahy 1996). The content of dry matter and protein can impact metabolism and its products, indirectly influencing the formation of carotenoids (Romberger and Norton 1961; McAvoy and Janes 1990).

Based on the measurement results and statistical results, there was a relationship between the nutrient content of potatoes, the values determining their colour and the applicability of FD process.

Conclusion

The structural stability of freeze-dried potatoes is significantly influenced by the amount of protein present. Starch and reducing sugars have little or no effect. The quantity of dry weight protein determines the raw potato luminance and the b^* value, which is dependent on the amount of carotenoids. There is typically an inverse relationship between starch content and protein. Furthermore, a strong correlation was found between the a^* value measured during colour measurements and other factors. The colour is correlated with the amount of dry weight protein which determines the quality of rehydrated freeze-dried potatoes. According to the results of principal component analysis, there are enough three variables to determinate to keep boiled potatoes sufficiently stable after applying FD. The results of the palatability test and the rehydration test are consistent with those obtained in the structural stability test. In addition to the results of the nutrient analysis, the results of the raw and boiled colour measurement can be used to select the appropriate variety. The potato varieties with a high protein content, calculated on dry matter, are lighter and yellower when boiled and are suitable for application of the FD method.

Based on our study, potato varieties that are suitable for processing by freeze-drying technology can be easily selected and this study provides information for food industry and agricultural production and may help breeders to achieve their agricultural production targets.

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Data Availability The data that support the findings of this study are available on request from the corresponding author (repas.zoltan@agr.unideb.hu; zoltan_repas@yahoo.com).

Declarations

Compliance with Ethics Requirements This article does not contain any studies with human or animal subjects.

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References

2R Core Team. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. 2022. Available online: https://www.R-project.org/ (accessed on 26 January 2023).

Arvanitoyannis IS, Vaitsi O, Mavromatis A (2008) Physico-chemical and sensory attributes in conjunction with multivariate analysis of two potato (Solanum tuberosum L.) cultivars after 90 days of storage: an exploratory authentication study. Int J Food Sci Tech 43:1960–1970

Bao H, Zhou J, Yu J, Wang S (2021) Effect of drying methods on properties of potato flour and noodles made with potato flour. Foods 10:1115

Bailey T, Franczyk AJ, Goldberg EM, House JD (2023) Impact of cooking on the protein quality of Russet potatoes. Food Sci & Nutn 11:8131–8142

Bárta J, Bártová V, Zdráhal Z, Sedo O (2012) Cultivar variability of patatin biochemical characteristics: table versus processing potatoes (Solanum tuberosum L.). J Agric Food Chem 60:4369–4378

Brown CR (2005) Antioxidants in potato. Am J Potato Res 82:163–172

Burlingame B, Mouillé B, Charrondiere R (2009) Nutrients, bioactive non-nutrients and anti-nutrients in potatoes. J Food Com Anal 22:494–502

Burlingame B, Mouillé B, Charrondiere R (2009b) Nutrients, bioactive non-nutrients and anti-nutrients in potatoes. J Food Compos Anal 22:494–502

Buzera A, Gikundi E, Orina I, Sila D (2022) Effect of pretreatments and drying methods on physical and microstructural properties of potato flour. Foods 11:507

Cai C, Lin L, Man J, Zhao L, Wang Z, Wei C (2014) Different structural properties of high-amylose maize starch fractions varying in granule size. J Agric Food Chem 62:11711–11721

Chen L, McClements DJ, Zhang H, Zhang Z, Jin Z, Tian Y (2019) Impact of amylose content on structural changes and oil absorption of fried maize starches. Food Chem 287:28–37

Copeland L, Blazek J, Salman H, Tang MC (2009) Form and functionality of starch. Food Hydrocolloids 23(6):1527–1534

Chung H, Li X, Kalinga D, Lim S, Yada R, Liu Q (2014) Physicochemical properties of dry matter and isolated starch from potatoes grown in different locations in Canada. Food Res Int 57:89–94

Defense Logistics Agency. The Nation's Combat Logistics Support Agency. Available online: https://www.dla.mil/Portals/104/Documents/TroopSupport/Subsistence/Rations/pcrs/misc/dehybib/b053b.pdf (accessed on 10 September 2023).

Dhital S, Shrestha AK, Hasjim J, Gidley MJ (2011) Physicochemical and structural properties of maize and potato starches as a function of granule size. J Agric Food Chem 59:10151–10161

Dincer I. (2003) Refrigeration systems and applications., John Wiley & Sons, England 534–536

FAO DATA https://www.fao.org/faostat/en/#data (accessed on 10 September 2023).

Faulks RM, Griffiths NM (1983) Influence of variety, site and storage on physical, sensory and compositional aspects of mashed potato. J Sci Food Agric 34:979–986

Fogelman E, Oren-Shamir M, Hirschberg J, Mandolino G, Parisi B, Ovadia R, Tanami Z, Faigenboim A, Ginzberg I (2019) Nutritional value of potato (Solanum tuberosum) in hot climates: anthocyanins, carotenoids, and steroidal glycoalkaloids. Planta 249:1143–1155

Guedes JS, Santos KC, Castanha N, Rojas ML, Junior MDM, Lima DC, Augusto PE (2021) Structural modification on potato tissue and starch using ethanol pre-treatment and drying process. Food Structure 29:100202

Guilford JP (1950) Fundamental statistics in psychology and education, 2nd edn. McGraw-Hill

Hoover R (2001) Composition, molecular structure, and physicochemical properties of tuber and root starches: a review. Carbohydr Polym 45:253–267

Hormdok R, Noomhorm A (2007) Hydrothermal treatments of rice starch for improvement of rice noodle quality. Lwt 40:1723–1731

Jarvis MC, Duncan HJ (1992) The textural analysis of cooked potato. 1. Physical principles of the separate measurement of softness and dryness. Potato Res 35:83–91

Jarvis MC, Mackenzie E, Duncan HJ (1992) The textural analysis of cooked potato. 2. Swelling pressure of starch during gelatinisation. Potato Res 35:93–102

Jia Y, Khalifa I, Hu L, Zhu W, Li J, Li K, Li C (2019) Influence of three different drying techniques on persimmon chips' characteristics: a comparison study among hot-air, combined hot-air-microwave, and vacuum-freeze drying techniques. Food Bioprod Process 118:67–76

Jitsuyama Y, Tago A, Mizukami C, Iwama K, Ichikawa S (2009) Endogenous components and tissue cell morphological traits of fresh potato tubers affect the flavor of steamed tubers. Am J Potato Res 86:430–441

Knorr D (1982) Effects of recovery methods on the functionality of protein concentrates from food processing wastes 1. J Food Process Eng 5:215–230

Leo L, Leone A, Longo C, Lombardi DA, Raimo F, Zacheo G (2008) Antioxidant compounds and antioxidant activity in "early potatoes. J Agric Food Chem 56:4154–4163

Li J, Liu G, Zhu X, Wang M, Li W, Wang W, Hu A, Zheng J (2023) Effects of NaCl and sucrose on the structural and functional properties of debranched quinoa starch-oleic acid complexes under baking. Int J Biol Macromol 226:1588–1596

Lumivero (2024). XLSTAT statistical and data analysis solution. https://www.xlstat.com/en.

Martens HJ, Thybo AK (2000) An integrated microstructural, sensory and instrumental approach to describe potato texture. Lwt 33:471–482

McAvoy RJ, Janes HW (1990) Glucose metabolism and pyridine nucleotide levels in potato tubers treated with ethylene. J Plant Physiol 135:759–762

Morris WL, Ducreux L, Griffiths DW, Stewart D, Davies HV, Taylor MA (2004) Carotenogenesis during tuber development and storage in potato. J Exp Bot 55:975–982

O'Carra P, Mulcahy P (1996) Lactate dehydrogenase in plants: distribution and function. Phytochemistry 42:581–587

Pan DD, Jane J (2000) Internal structure of normal maize starch granules revealed by chemical surface gelatinization. Biomacromol 1:126–132

Pots AM, Gruppen H, de Jongh HH, van Boekel MA, Walstra P, Voragen AG (1999) Kinetic modeling of the thermal aggregation of patatin. J Agric Food Chem 47:4593–4599

Pots AM, ten Grotenhuis E, Gruppen H, Voragen AG, de Kruif KG (1999) Thermal aggregation of patatin studied in situ. J Agric Food Chem 47:4600–4605

Qiu G, Jiang Y, Deng Y (2019) Drying characteristics, functional properties and in vitro digestion of purple potato slices dried by different methods. J of Int Agr 18:2162–2172

Ratti (2013) C. 3-Freeze drying for food powder production. In Handbook of Food Powders; Woodhead Publishing Series in Food Science, Technology and Nutrition; Bhandari, B., Bansal, N., Zhang, M., Schuck, P., Eds.; Woodhead Publishing Witney: Oxford, UK, 57–84.

Répás Z, Prokisch J, Győri Z, Sipos P (2023) The relationship between rehydration time and tenderness at different rehydrating water tempera-tures in freeze-dried pork loin. Processes 11:2822

Romberger JA, Norton G (1961) Changing respiratory pathways in potato tuber slices. Plant Physiol 36:20

Sablani SS (2006) Drying of fruits and vegetables: retention of nutritional/functional quality. Drying Technol 24:123–135

Smith MF, Leighton CS, Morey L, Schönfeldt HC (2009) Application of partial least squares regression to relate tastiness of boiled potatoes to chemical and physical tests. S Afr J of Plant and Soil 26:31–35

Sulli M, Mandolino G, Sturaro M, Onofri C, Diretto G, Parisi B, Giuliano G (2017) Molecular and biochemical characterization of a potato collection with contrasting tuber carotenoid content. PLoS ONE 12:e0184143

Shewry PR (2003) Tuber storage proteins. Ann Bot 91:755–769

Thybo AK, Christiansen J, Kaack K, Petersen MA (2006) Effect of cultivars, wound healing and storage on sensory quality and chemical components in pre-peeled potatoes. Lwt 39:166–176

Tüfekçi S, Özkal SG (2023) The optimization of hybrid (microwave–conventional) drying of sweet potato using response surface methodology (RSM). Foods 12:3003

Vamadevan V, Bertoft E (2015) Structure-function relationships of starch components. Starch-Stärke 67:55–68

van Koningsveld GA (2001) Physico-chemical and functional properties of potato proteins. Wageningen University and Research

Van Marle JT, de Vries RVDV, Wilkinson EC, Yuksel D (1997) Sensory evaluation of the texture of steam-cooked table potatoes. Potato Res 40:79–90

Waghmare RB, Perumal AB, Moses JA, Anandharamakrishnan C (2021) Recent developments in freeze drying of foods Reference Module in Food Science ISBN: 9780128157817

Wolters AA, Uitdewilligen JG, Kloosterman BA, Hutten RC, Visser RG, van Eck HJ (2010) Identification of alleles of carotenoid pathway genes important for zeaxanthin accumulation in potato tubers. Plant Mol Biol 73:659–671

Woolfe JA, Poats SV (1987) The potato in the human diet. Cambridge University Press

Waglay A, Karboune S, Alli I (2014) Potato protein isolates: recovery and characterization of their properties. Food Chem 142:373–382

Zhou X, McQuinn R, Fei Z, Wolters AA, Van Eck J, Brown C, Giovannoni JJ, Li LI (2011) Regulatory control of high levels of carotenoid accumulation in potato tubers. Plant, Cell Environ 34:1020–1030