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Nutritional Value of Jerusalem Artichoke Tubers (*Helianthus tuberosus* L.) Grown in Organic System under Lithuanian and Polish Conditions

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Abstract: The aim of the study was to assess the nutritional value of *H. tuberosus* tubers grown in the organic farming system in Poland and Lithuania. The work was based on field experiments carried out in 2015–2017 in Parczew (Poland) and Akademija (Lithuania). The experiments were carried out using the randomized block method in four replications. Two cultivars of Jerusalem artichoke (JA) 'Albik' and 'Rubik' were tested. After the harvest of tubers, an assessment of their quality was carried out by standard methods. Due to the relocation of JA cultivation from Central and Eastern Europe to Northeast Europe, there were changes in the chemical composition of *H. tuberosus* tubers. The tubers from crops in Lithuania were characterized by a lower content of inulin, crude fiber and protein, ascorbic acid, total and endogenous amino acids than in Poland, but a higher content of true protein and macroelements. Edaphic factors determined, to a greater extent than genetic factors, the nutritional value of tubers. Assessment of the influence of varietal characteristics, meteorological conditions, and geographic location on the amount of biologically active compounds in JA will allow growers and consumers to choose the most suitable cultivars.

Keywords: Jerusalem artichoke (JA); cultivar; geographic location; varietal variability; phenotypic variability; environmental variability; chemical composition of tubers; nutritional value

1. Introduction

Tubers of JA are considered quality food in Western Europe, and recently also in Central-Easter and North-East of Europe, as a very tasty, juicy vegetable, delicate, sweet, tasting like artichokes or asparagus. Interest in JA tubers, intended for human consumption, is an effect of their chemical composition, among others: inulin and fructo-oligosaccharides, characterizing the natural properties and fructose, minerals, essential amino acids, vitamins, and flavonoids. Fructo-oligosaccharides are characterized by prebiotic properties. Inulin, in turn, in the human body is hydrolyzed to fructose, and safe for diabetics. JA, due to favorable chemical composition of tubers and sensory quality, arouses increasing interest [1–4]. It is able to partially or completely replace scarce raw materials, as well as allow the widening of a range of manufactured products, including functional foods. The advantage of JA is that it tolerates drought and frost, and has small requirements in terms of climate, soil, and care. The optimum temperature for tuber growth is between

15–20 °C. This species is relatively tolerant to drought and its water use ratio ranges from 1.1-1.9 g of dry matter per 1 kg of water. In the process of photosynthesis, JA uses large quantities of CO_2 to produce sugars. During long-term drought, their growth is usually limited (to 1–1.5 m) and the plants form small tubers. For JA cultivation, not only good and average soils are suitable, but also light, loamy sands, and loose sands. The soil acidity that JA tolerates is 4.5–8.2 [4–6]. Medium and weak soils with unregulated acidity in Poland account for over 60%, and in Lithuania about 70%, so in both these countries, the potential for the cultivation of *H. tuberosus* is large. The very well-developed JA root system enables the cultivation of this species in areas with poorer soils and in neglected and abandoned soils.

Flowering timing of *H. tuberosus* was found to have a clear influence on genetic crosses; Žaldarienė [7] assessed the flowering duration of many clones monitored over two consecutive growing seasons. Danilčenko et al. [8] proved that the distribution of macronutrients in *H. tuberosus* tubers is largely related to the degree of organogenesis. Kays and Kultur [9] described the phenological flowering dates and flowering durations of 190 cultivated forms from Georgia and the USA. There was considerable genetic variation in flowering date and time (69 to 174 days after planting) (DAP). Their flowering time ranged from 21 to 126 days. The beginning of flowering turned out to be significantly modified by the planting date and location (geographical location). They suggest that at higher latitudes, under controlled growth conditions, it is possible to synchronize the flowering of some clones of this species. Both flowering and tuberization, however, are modified by the photoperiod [7,9–11]. Hence, the flowering variability of plants in different geographical conditions can be assumed; with different photoperiods, it may affect not only the yield, but also its quality. Therefore, the purpose of the study was to assess the nutritional value of tubers of *H. tuberosus* grown in organic farming system in both countries (Poland and Lithuania).

Research hypothesis: assume that the chemical composition of tubers, and in particular the content of inulin, protein, amino acids, and antioxidants in different genotypes of organically cultivated JA depend on climatic and soil conditions and geographic location (cultivation location).

The aim of the research is to determine and evaluate the chemical composition of tubers, including the amount of inulin, proteins, amino acids, fibers and crude fat, certain antioxidants, and macronutrients in various genotypes of JA under different geographical conditions.

2. Materials and Methods

Field experiments were conducted in 2015–2017 in Poland (Parczew) (51°38′ N; 22°54′ E) and Lithuania—Experimental Field Station in Akademija (54°53′ N, 23°50′ E). The experiments were performed using randomized blocks in four replications on a fawn soil, produced from strong clay loam [12]. The tested physical and chemical properties of the soils are given in Table 1. The following two cultivars of JA were used in both experiments: 'Albik' and 'Rubik'. JA was grown on the field off rotation, forecrop was winter triticale. Tubers were planted in spring, 26–27 April, every 40 cm in a row, and the distance between the rows was 62.5 cm. The area of each plot was 20 m^2. JA was grown organically. Therefore, the principles of Good Manufacturing Practice were applied. In the current system, the products are manufactured and controlled consistently to quality standards. It is designed to reduce product pollution risk. Therefore, each year of vegetation was fertilized with organic granular organic fertilizers. Their composition is as follows: nitrogen (N)—3.6%, phosphorus (P)—2.8%, potassium (K)—2.2%, calcium (Ca)—2%, magnesium (Mg)—1.5%, iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), cobalt (Co), sodium (Na). The C/N ratio was 9 and the pH was 6.4. In each year of the study, the agrochemical parameters of the soil remained almost unchanged in both spring and autumn JA harvest. Therefore, the fertilization dose was about 500 kg ha^{-1} of the current granulated fertilizer (according to soil analyses) [7]. JA, as a rapidly growing species, competitive to weeds, requires weed control only from the moment of plantation establishment to the closure of the field [7]. Hence, mechanical weed control by harrowing was applied in early spring, when the soil was dry. During the experiment, pesticides were not used in agrotechnics because JA is sufficiently resistant to diseases and pests. Before digging, the plant stems were cut, shredded, and spread on the soil as fertilizer. The tubers were harvested in autumn, at the end of November.

Table 1. Physical and chemical properties of soils in Akademija and Parczew (2015–2017).

Year	Content of Assimilable Macronutrients ($mg \cdot 100\ g^{-1}$ Soil)			Humus Content (%)	pH (KCl)	Micronutrient Content ($mg \cdot 1\ kg^{-1}$ Soil)				
	P_2O_5	K_2O	Mg			Cu	Mn	Zn	Fe	B
				Akademija						
2015	20.1	19.3	8.1	1.6	6.9	8.8	332.0	58.7	3876.0	7.8
2016	22.3	21.1	7.9	1.9	6.4	7.1	346.0	54.3	3697.0	6.7
2017	19.9	21.6	7.3	1.7	6.5	6.5	321.0	49.9	3801.0	7.1
Average	21.2	20.7	7.8	1.8	-	7.5	333.0	54.3	3791.0	7.2
				Parczew						
2015	20.1	13.1	7.8	0.9	5.9	7.51	318.0	40.1	3760	7.2
2016	18.9	10.9	7.0	1.1	5.8	4.92	337.0	56.7	3925	5.3
2017	24.0	11.8	6.3	1.0	6.6	8.99	166.0	41.1	3600	6.0
Average	21.0	11.9	7.03	1.0	-	7.02	274.0	46.0	3762	6.2

Source: Own results from in the Laboratory Central of Agro-Ecological (CLA), the University of Life Science in Lublin; Laboratory of Food Raw Materials, and the Agrochemical Research Laboratory of the Lithuanian Research Centre for Agriculture and Forestry in Kaunas.

2.1. Characteristic of Cultivars

Both tested cultivars were bred at the Plant Breeding and Acclimatization Institute in Radzików (Poland) by Prof. Stanislaw Góral. They were registered on the list of cultivars in the national register in Poland, in 1997 [13,14].

The 'Albik' cultivar is characterized by a medium-scatter habit, a stem up to 2.5–3 m high, of medium thickness, oval-heart-shaped leaves, very pointed, with medium-length petioles, serrated edges of the leaf blades; an inflorescence on the tops of the main and lateral branches; yellowish flowers; oval-oblong to club-shaped tubers, cream skin, and white flesh. The tubers are clustered, set on short stolons and are difficult to separate from the root (Figure 1). This cultivar gives tuber yield from 24 tha^{-1} on the soils of IV valuation class to 34 $t \cdot ha^{-1}$ on the medium soils (valuation class III). The yield of green mass of this cultivar is twice as high as that of tubers [5,15].

The 'Rubik' cultivar is characterized by a medium-scatter habit, with stems approx. 3 m high: oval-heart-shaped leaves with pointed tips, yellow flowers. The ends of stolons produce pale red tubers with an even, ovoid shape and white flesh (Figure 2) [13,14]. The cultivar yields 23–30 $t \cdot ha^{-1}$ tubers, and in very good conditions, even 40 $t \cdot ha^{-1}$ [5,15].

2.2. Methodology of Soil Testing

Soil samples were taken each year at the beginning and at the end of vegetation of JAs with Nekrasov auger from randomly chosen 5 places at depths of 0–20 cm. Soil granulometric composition was determined by means of the aerometric method by Prószyński [16,17]. The following soil quality indicators were determined: pH—1 mol per l-1 KCl in suspension according to ISO 10390 (2005); the amounts of available phosphorus (P_2O_5) and available potassium (K_2O), by employing the Egner-Rhyming-Domingo (A-L) method [17]. Analysis of microelements was performed using the atomic absorption spectrometry (ASS); amount of humus by the Thurin method [18].

2.3. Methodology of Tuber Sampling

At the time of harvest, tuber samples were taken for chemical analysis (3 kg each), Three samples were taken from each plot (2 cultivars × 4 replicated blocks at each site (2) × 3 = 48 samples). Chemical analysis of the fresh material was carried out immediately after harvest. Chosen samples of tubers were washed and chopped [4].

Figure 1. Tubers, stolons, roots, and rhizomes of the 'Albik' cultivar (*H. tuberosus* L.). Source: own photo.

Figure 2. Tubers, stolons, roots, and rhizomes of the 'Rubik' cultivars of *H. tuberosus*. Source: own photo.

2.4. Methods for Research and Analysis

Laboratory analyses of the chemical composition of JA were performed for each sample of the experiment [19]. Standard methods were used for each analytical determination. The analyses were made at the Central Ecological Laboratory of the University of Life Sciences in Lublin and at the Laboratory of Food Raw Materials, Agronomic and Zootechnical Research at Vytautas Magnus University Agriculture Academy, as well at the Agrochemical Research Laboratory of the Lithuanian Research Centre for Agriculture and Forestry. The tuber samples were washed with tap water, weighed, and air-dried for 24 h to reduce water content. All samples were oven-dried at 70–80 °C for 24 h. The dried material was ground on a GRINDOMIX GM 200 knife-mill. The obtained powder was packed in airtight containers prior to use. The content of dry matter (DM) was determined by drying samples to a constant weight at a temperature of 105 °C [20].

The content of crude fat (%) was determined according to the official methods of analysis of AOAC [21], in duplicate measurements: methods 925.09, 923.03, and 945.38, respectively; crude fiber (%)—according to the Heneberg-Shtoman method [22]. Nitrogen content (%) was determined using the Kjeldahl method, AOAC 981.10 [23]. Crude and true protein content (%) was calculated with conversion factor 6.25. A nitrogen-to-protein conversion factor was chosen, set at 6.25 as an official factor in most trade and food regulations [24]. A spectrophotometric method was used for the analysis of inulin (%) in JA tubers [25]. The inulin was extracted from raw material by the accelerated solvent extraction method, before subsequent hydrolysis in acid condition. The hydrolysates were then analyzed for fructose by means of spectrophotometry. The spectrophotometric method was based on oxidation of fructose by periodate and evaluation of the remaining periodate by measurement of absorbance at 350 nm of the triiodide complex formed upon addition of potassium iodide. The optimum conditions for the detection of fructose were 1 mmol L^{-1} periodate and 1.5 mmol L^{-1} potassium iodide at pH 6. The amino acid ($g \cdot kg^{-1}$) composition was determined by ion-exchange chromatography after 24 h of hydrolysis with 6N HCl at 110 °C. After cooling down, filtering, and washing, the hydrolyte was evaporated in a vacuum evaporator at a temperature below 50 °C. The dry residue was dissolved in a buffer of pH 2.2. The prepared sample was analyzed with the use of the ninhydrin method [26,27]; pH 2.6, 3.0, 4.25, and 7.9 buffers were applied. The ninhydrin solution was buffered at pH 5.5. The hydrolyzed amino acids were determined with an AAA-400 analyser (INGOS, Prague Czech Republic). A photometer working with two wavelengths—440 and 570 nm—was used. A column measuring 350 × 3.7 mm in height, packed with an Ostion LG ANB ion exchanger (INGOS, Prague, Czech Republic), was utilized as a detector. Column temperature was kept at 60–74 °C and that of the detector at 121 °C. The calculations were carried out according to the external standard. The content of P, K, Mg, Ca, and Na were determined by inductively coupled plasma atomic emission spectrometry (ICP-AES). The procedures were performed according to the standard method [28].

In fresh tubers, the content of soluble dry matter (%) was determined with hand refractometer ATAGO [29] and content of vitamin C (mg per 100 g^{-1}) by titrating with 2,6-dichlorophenolindophenol sodium salt [30].

2.5. Statistical Analyses

The results were statistically analysed mainly by analysis of variance (ANOVA). The significance of the sources of variation was tested by the Fisher-Snedecor F-test, and the significance of differences between the averages compared was performed using multiple Tukey intervals. Then the empirical of mean square values obtained from the analysis of variance were compared with their expected values. Solving the equations using this method, the estimation of variance components corresponding to individual sources of variability was obtained. The mutual relations between the evaluations of the variance components and their percentage structure were the basis for the assessment of the influence of the studied cultivars, years, and geographic location on the variability of the chemical composition of JA tubers. The function parameters were determined by the least-squares method. To determine the percent contributions of the individual sources of variation and their interactions to the total variation of the investigated traits, estimation of variance components was performed, where:

– σ_e^2 is the estimation of environmental variation associated with the repeating of observations or measurements over time;
– σ_L^2 is the estimation of locality variation;
– σ_p^2 is the estimation of (total) phenotypic variation [31].

Correlations between the derived estimations of the variance components and their percentage structure formed the basis for evaluations of the effects of the locality and year factors on the variation of the investigated traits. Coefficients of variation of the studied traits were also calculated using SAS software [32].

2.6. Geographic Location

The village of Akademija is located in the central part of the country on the Central-Lithuanian Plain on the Neuman's River and to the west of the Kaunas reservoir (Figure 3). In the village of Akademija, the soils under cultivation can be classified as Haplic Luvisol [12]. On the loam of Haplic Luvisol, however, the humus content is around 2.0%, and the soil pH is slightly acidic. According to the SPI results, droughts in the Akademija region occur in 15% of all months in the Kaunas region, and wet periods—in 16% of all assessed months. According to the SPI assessment, 70% of the total months in the study period in Kaunas were almost normal. The probability of an extremely dry period in Lithuanian climatic conditions is quite low—3.0% in central Lithuania [33].

Figure 3. Geographical location of Akademija.

Geographically, the village of Parczew lies in the Polesie Lubelskie area, in the Lubelskie Province in Poland (Figure 4). The dominant soil in this village was developed on clay and sandy tracks of water-glacial origin, mainly boulder clay and sands. Luvisols are defined as the average quality of the soil. The area of Parczew lies within the Lubartowsko–Parczewska Climate Area. It is characterized by significant values of water evaporation (860–900 mm a year), high average annual relative air humidity (68–70%), high wind speeds (3.0–3.5 m/s), and relatively large annual temperature anomalies air (1.2–1.4 °C) [34].

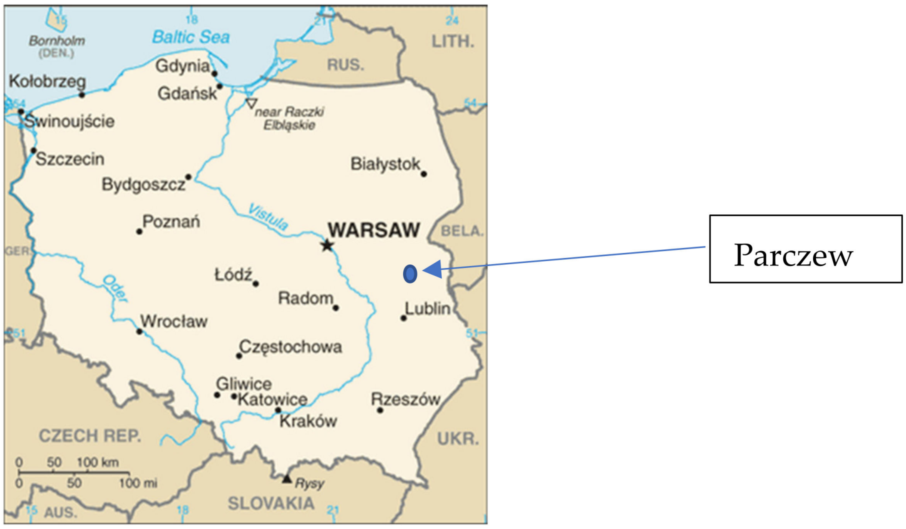

Figure 4. Geographical location of Parczew.

3. Results

3.1. Soil Conditions

This soil in the experimental fields of Akademija exhibited the following characteristics: neutral, medium humus, limnoglacial loam on moraine loam, and calcareous deeper gleyic Luvisol (Calearie Luvisol) [12]. It was rich in phosphorus and potassium; medium in magnesium and copper; and medium in manganese, iron, and zinc. The average acidity of the soil in a solution of KCl was 6.4 to 6.9 pH, which allowed the classification of the soil as slightly acidic. The humus content in the arable layer was medium and formed at 1.6–1.94% (Table 1). Field experiments in Parczew were carried out on sandy loam soil with clay sand granulometric composition (i.e., light soil) [12].

In terms of agricultural usefulness, these soils belong to a slightly acidic good rye complex. The soil content included the following assimilable components: very high in phosphorus and magnesium; high in assimilable boron; and medium in potassium, copper, manganese, iron, and zinc. The average soil acidity in KCl solution was 5.77 to 6.0 pH, which classified the experimental soil as slightly acidic. The content of humus in the crop layer was low and amounted to 0.94–1.06% (Table 1).

3.2. Meteorological Conditions

The meteorological conditions in Akademija (Lithuania) were very varied. Significant fluctuations in both air temperature and precipitation were observed in all the years of the study (Tables 1 and 2). In 2015, both air temperature and rainfall were well below the long-term average. The year 2016, initially with excessive humidity, turned into a very dry year. In 2016, spring was warm. The period of active plant growth began on average 10 days earlier than usual and ended on average 2 weeks earlier than usual. The growing season lasted a week shorter than the long-term data (192, and the long-term average was 199). The temperatures in March, April, and May exceeded the standard climatic norm (hereinafter SCN) by 0.1°C to 2.0 °C. In spring, more rainfall was recorded in March—37% more compared to the SCN. The meteorological conditions at the beginning of active growth were not conducive to the sprouting of JA. In the winter season, the temperatures varied, and the negative air temperatures in the last winter month increased by 4.8 °C above the average long-term climatic normality. The fall season was characterized by abundant rainfall—85 mm more compared to the SCN. The air temperature in March 2017 was 3.2 °C higher than in a normal standard climate, with April and May being cooler with temperatures ranging from 0.9 to 1.6 °C below the SCN. Precipitation in spring was 18% higher compared to the long-term norm, which allowed *H. tuberosus* tubers to germinate in the soil. Summer and autumn can be called a particularly humid period, when rainfall fell by as much as 35–74% compared to many years of rainfall. 2017 was notable as the year of excess moisture according to HTC (>1.6). Conditions were unfavourable during the period of growth. When the leaves grew and started to bloom, there was a lot of moisture (Tables 2 and 3).

Table 2. The course of air and rainfall temperatures (2015–2017) obtained from the meteorological station in Akademija (Lithuania) and Parczew (Poland).

Year	Temperature/Rainfall	Months									Average/Sum
		March	April	May	June	July	August	September	October	November	
						Akademija					
2015	Temperature (°C)	0.3	5.7	12.2	15.6	17.2	16.6	12.8	6.8	1.1	9.8
	Rainfall (mm)	40.0	37.2	52.5	61.3	73.6	73.6	51.7	49.3	44.2	483.3
2016	Temperature (°C)	0.3	6.7	12.6	15.6	17.6	17.1	12.2	7.1	1.9	10.1
	Rainfall (mm)	41.3	38.1	47.2	66.7	83.0	73.2	53.8	54.8	48.2	506.3
2017	Temperature (°C)	0.5	6.7	12.6	15.6	17.6	16.9	12.2	7.2	1.9	10.1
	Rainfall (mm)	40.4	38.0	48.4	67.2	83.7	74.0	52.7	55.2	47.6	507.2
SCN (1974–2013)	Temperature (°C)	1.0	7.4	13.0	16.3	18.0	17.2	12.6	7.6	2.6	10.6
	Rainfall (mm)	28.0	39.0	60.7	65.9	82.0	70.7	53.7	40.1	38.2	478.3
						Parczew					
2015	Temperature (°C)	5.2	6.9	13.5	17.6	17.2	18.7	12.2	7.7	1.7	11.2
	Rainfall (mm)	31.4	15.8	98.2	61.6	118.1	50.8	49.1	40.4	60.2	525.2
2016	Temperature (°C)	2.5	8.8	12.3	16.0	18.1	17.9	12.2	8.7	3.3	11.1
	Rainfall (mm)	60.9	32.1	35.5	83.2	43.0	99.3	27.0	69.8	30.3	481.1
2017	Temperature (°C)	0.9	8.6	12.6	14.8	18.4	16.9	13.8	5.4	3.9	10.6
	Rainfall (mm)	47.4	38.0	42.0	107.4	83.8	87.5	28.3	101.0	75.3	610.7
SCN * (1951–2010)	Temperature (°C)	0.5	6.7	12.6	15.6	17.6	16.9	12.2	7.2	1.9	10.1
	Rainfall (mm)	40.4	38.0	48.4	67.2	83.7	74.0	52.7	55.2	47.6	507.2

* SCN—standard climatic norm; Source: Own study based on data from meteorological stations in Uhnin (Poland) and the Academy (Lithuania).

Table 3. The value of the Sielyaninov Hydrothermal Coefficient (SHC) for meteorological stations at Akademija and Parczew (2015–2017).

Month	Years					
	2015	2016	2017	2015	2016	2017
		Akademija			Parczew	
April	2.2	1.9	1.9	0.8	1.2	1.5
May	1.4	1.2	1.2	2.3	0.9	1.1
June	1.3	1.4	1.4	1.2	1.7	2.4
July	1.4	1.5	1.5	2.2	0.8	1.5
August	1.5	1.4	1.5	0.9	1.8	1.7
September	1.3	1.5	1.4	1.3	0.7	0.7
October	2.3	2.5	2.5	1.7	1.8	3.4
Average	1.6	1.6	1.5	1.5	1.3	1.7
Average 1974–2013		1.5			1.6	

Source: Data from meteorological stations in Parczew (Poland) and Akademija (Lithuania); range of values of this index were classified according to Selyaninov as: extremely—$k \leq 0.4$; very dry—$0.4 < k \leq 0.7$; dry—$0.7 < k \leq 1.0$; fairly dry—$1.0 < k \leq 1.3$; optimum—$1.3 < k \leq 1.6$; fairly humid—$1.6 < k \leq 2.0$; wet—$2.0 < k \leq 2.5$; very humid—$2.5 < k \leq 3.0$; extremely humid—$k > 3.0$.

The Selyaninov's Hydrothermal Coefficient (SHC), expressed as the quotient of the monthly sum of rainfall and the sum of average daily air temperatures in a given month for the period in which the average daily air temperature exceeds 10 °C, indicates that the meteorological conditions in Lithuania (Akademija) were more favourable for JA cultivation than in Poland (Parczew). At the station in Parczew (Poland), drought took place in April and August 2015, in May 2016, and in September 2016 and 2017 (Tables 2 and 3). The growing season of *H. tuberosus* in this region lasts for an average of 208 days. The earliest beginning of vegetation and optimal climatic conditions for growth is the moment of reaching SHC of 1.6–1.8 (conditions of excessive humidity). Optimal climatic conditions for mass flowering is observed when the SHC drops to 1.0–0.8, then mass flowering begins even 10 days earlier and lasts 30 days longer.

3.3. Chemical Composition of Tubers

The chemical composition of *H. tuberosus* tubers were varied, depending on geographic location, cultivar characteristics, and years (Tables 4 and 5, Figure 3). Dry matter content in *H. tuberosus* tubers was on average 22.56%, soluble dry matter 18.88% DM, fiber content 4.54%, fat content 0.20%, crude protein 10.47%, true protein 6.71% of DM. Inulin constituted on average 17.16% of FM tubers (Table 4). Endogenous amino acids accounted for 56.72%, and exogenous 43.22% of total amino acids. Ascorbic acid accounted for only 5.5 mg· 100 g^{-1} of fresh weight of tubers, and total nitrogen content was on average 11.34 g·kg^{-1}, content of phosphorus 3.35 g, potassium 30.08 g, magnesium 1.65 g, calcium 0.75 g, and sodium 0.18 g·kg^{-1} DM. The average value of these features and their coefficients of variation are shown in Figure 5.

Table 4. Chemical composition of *H. tuberosus* tubers depending on geographic location and cultivars (2015–2017 average).

Features	Akademija			Parczew			Cultivars	
	Albik	Rubik	Average	Albik	Rubik	Average	Albik	Rubik
Dry mass (%)	24.08 ^{a*}	21.10 ^{b}	22.59 ^{a}	23.53 ^{a}	21.52 ^{b}	22.53 ^{a}	23.81 ^{a}	21.31 ^{b}
Soluble dry mass (%)	22.18 ^{a}	15.40 ^{b}	18.79 ^{a}	21.34 ^{a}	16.60 ^{b}	18.97 ^{a}	21.76 ^{a}	16.00 ^{b}
Inulin (FM) (%)	17.71 ^{b}	13.49 ^{b}	15.60 ^{b}	19.29 ^{a}	18.15 ^{a}	18.72 ^{a}	18.50 ^{a}	15.82 ^{b}
Crude fibre (%)	3.70 ^{a}	3.24 ^{b}	3.47 ^{b}	5.20 ^{b}	6.03 ^{a}	5.62 ^{a}	4.45 ^{b}	4.64 ^{a}
Crude fat (%)	0.19 ^{b}	0.24 ^{a}	0.22 ^{a}	0.17 ^{b}	0.21 ^{a}	0.19 ^{b}	0.18 ^{b}	0.22 ^{a}
Crude protein (%)	10.99 ^{a}	7.87 ^{b}	9.43 ^{b}	11.07 ^{b}	11.95 ^{a}	11.51 ^{a}	11.03 ^{a}	9.91 ^{b}
True protein (%)	8.35 ^{a}	6.14 ^{b}	7.25 ^{a}	5.93 ^{b}	6.43 ^{a}	6.18 ^{b}	7.14 ^{a}	6.29 ^{b}
Total amino acids (g·kg^{-1})	51.95 ^{a}	41.38 ^{b}	46.67 ^{b}	52.27 ^{a}	44.69 ^{b}	48.48 ^{a}	52.11 ^{a}	43.04 ^{b}
Endogenous amino acids (g·kg^{-1})	29.92 ^{a}	22.26 ^{b}	26.09 ^{b}	30.31 ^{a}	25.44 ^{b}	27.88 ^{a}	30.12 ^{a}	23.85 ^{b}
Exogenous amino acids (g·kg^{-1})	22.03 ^{a}	19.01 ^{b}	20.52 ^{a}	21.96 ^{a}	19.25 ^{b}	20.61 ^{a}	22.00 ^{a}	19.13 ^{b}
Ascorbic acid (FM) (mg·100 g^{-1})	5.60 ^{a}	5.20 ^{b}	5.40 ^{a}	5.81 ^{a}	5.43 ^{b}	5.62 ^{a}	5.71 ^{a}	5.32 ^{b}
N (g·kg^{-1})	13.36 ^{a}	11.60 ^{b}	12.48 ^{a}	11.07 ^{a}	9.31 ^{b}	10.19 ^{b}	12.22 ^{a}	10.46 ^{b}
P (g·kg^{-1})	3.56 ^{a}	3.27 ^{b}	3.42 ^{a}	3.42 ^{a}	3.16 ^{a}	3.29 ^{b}	3.49 ^{a}	3.22 ^{b}
K (g·kg^{-1})	34.24 ^{a}	29.38 ^{b}	31.81 ^{a}	29.30 ^{a}	27.41 ^{a}	28.36 ^{b}	31.77 ^{a}	28.40 ^{b}
Mg (g·kg^{-1})	1.44 ^{b}	1.56 ^{a}	1.50 ^{b}	1.64 ^{b}	1.94 ^{a}	1.79 ^{a}	1.54 ^{b}	1.75 ^{a}
Ca (g·kg^{-1})	0.85 ^{a}	0.86 ^{a}	0.85 ^{a}	0.63 ^{b}	0.65 ^{a}	0.64 ^{b}	0.74 ^{a}	0.75 ^{a}
Na (g·kg^{-1})	0.23 ^{a}	0.17 ^{b}	0.20 ^{a}	0.17 ^{a}	0.15 ^{b}	0.16 ^{b}	0.20 ^{a}	0.16 ^{b}

* Letter indicators at averages determine the so-called homogeneous groups (statistically homogeneous). The occurrence of the same letter pointer at averages (at least one) means that there is no statistically significant difference between them.

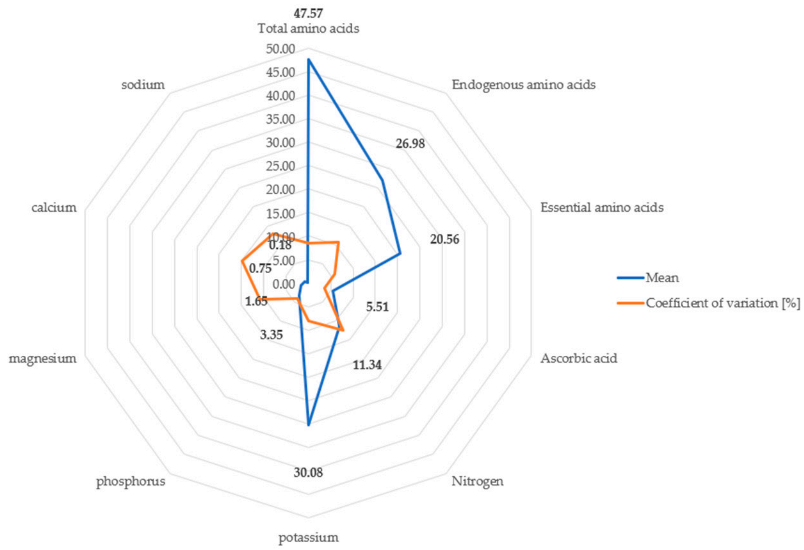

Figure 5. The variability of selected chemical constituents of JA tubers (Mean in g·kg^{-1}).

The genetic properties of the tested cultivars significantly influenced all the traits of chemical composition of the tubers (Table 4).

The average of the cultivar with a higher content of dry matter, soluble components, inulin, raw and proper protein, total amino acids, exogenous and endogenous amino acids, ascorbic acid, nitrogen, phosphorus, potassium, and sodium turned out to be 'Albik'. In turn, the 'Rubik' cultivar was characterized by a significantly higher content of crude fiber, crude fat, and magnesium than the 'Albik cultivar'. Only calcium content was independent of the varietal characteristics (Table 4).

Table 5. Influence of locality and years on the chemical composition of *H. tuberosus* tubers (average of varieties).

Features	Akademija				Parczew				Years		
	2015	2016	2017	Average	2015	2016	2017	Average	2015	2016	2017
Dry mass (%)	24.18 ^{a*}	22.23 ^{a}	21.36 ^{b}	22.59 ^{a}	23.63 ^{a}	22.56 ^{a}	21.40 ^{a}	22.53 ^{a}	23.91 ^{a}	21.38 ^{b}	22.64 ^{a}
Soluble dry mass (%)	22.37 ^{a}	15.60 ^{b}	15.20 ^{b}	18.79 ^{a}	21.31 ^{a}	19.00 ^{a}	16.59 ^{b}	18.97 ^{a}	21.84 ^{a}	15.90c	18.87 ^{b}
Inulin (FM) (%)	16.90 ^{a}	15.45 ^{a}	14.45 ^{b}	15.60 ^{b}	19.34 ^{a}	18.65 ^{a}	18.18 ^{a}	18.72 ^{a}	18.12 ^{a}	16.32 ^{b}	17.22 ^{a}
Crude fibre (%)	3.59 ^{a}	3.48 ^{a}	3.34 ^{b}	3.47 ^{b}	5.41 ^{a}	5.54 ^{a}	5.92 ^{a}	5.62 ^{a}	4.50 ^{b}	4.63 ^{a}	4.57 ^{a}
Crude fat (%)	0.21 ^{a}	0.25 ^{a}	0.20 ^{b}	0.22 ^{a}	0.16 ^{b}	0.21 ^{a}	0.20 ^{a}	0.19 ^{b}	0.19 ^{b}	0.20 ^{a}	0.19 ^{b}
Crude protein (%)	11.03 ^{a}	9.11 ^{b}	8.15 ^{b}	9.43 ^{b}	11.94 ^{a}	11.55 ^{a}	11.02 ^{a}	11.50 ^{a}	11.49 ^{a}	9.59c	10.54 ^{b}
True protein (%)	8.06 ^{a}	7.24 ^{b}	6.46 ^{b}	7.25 ^{a}	6.34 ^{a}	6.05 ^{a}	6.16 ^{a}	6.18 ^{b}	7.20 ^{a}	6.31 ^{b}	6.76 ^{b}
Total amino acids ($g \cdot kg^{-1}$)	51.99	46.60	41.43	46.67 ^{a}	52.01 ^{a}	48.18 ^{a}	45.26 ^{b}	48.48 ^{a}	52.00 ^{a}	43.35 ^{b}	47.67 ^{b}
Endogenous amino acids ($g \cdot kg^{-1}$)	28.57 ^{a}	25.24 ^{a}	24.45 ^{b}	26.09 ^{b}	31.23 ^{a}	26.87 ^{b}	25.53 ^{b}	27.88 ^{a}	29.90 ^{a}	24.99c	27.45 ^{b}
Exogenous amino acids ($g \cdot kg^{-1}$)	22.01 ^{a}	20.56 ^{a}	18.98 ^{b}	20.52 ^{a}	21.43 ^{a}	20.90 ^{a}	19.51 ^{a}	20.61 ^{a}	21.72 ^{a}	19.25 ^{b}	20.48 ^{a}
Ascorbic acid (FM) ($mg \cdot 100\ g^{-1}$)	5.56 ^{a}	5.29 ^{a}	5.34 ^{b}	5.40 ^{a}	5.91 ^{a}	5.56 ^{a}	5.39 ^{a}	5.62 ^{a}	5.74 ^{a}	5.37 ^{b}	5.55 ^{a}
N ($g \cdot kg^{-1}$)	13.20 ^{a}	12.34 ^{a}	11.89 ^{b}	12.48 ^{a}	11.09 ^{a}	10.40 ^{a}	9.08 ^{a}	10.19 ^{b}	12.15 ^{a}	10.49 ^{b}	11.32 ^{a}
P ($g \cdot kg^{-1}$)	3.44 ^{a}	3.60 ^{a}	3.23 ^{a}	3.42 ^{a}	3.51 ^{a}	3.21 ^{a}	3.16 ^{a}	3.29 ^{a}	3.48 ^{a}	3.20 ^{b}	3.34 ^{a}
K ($g \cdot kg^{-1}$)	33.86 ^{a}	31.65 ^{a}	29.91 ^{b}	31.81 ^{a}	29.58 ^{a}	28.40 ^{a}	27.10 ^{a}	28.36 ^{b}	31.72 ^{a}	28.51 ^{b}	30.11 ^{a}
Mg ($g \cdot kg^{-1}$)	1.39 ^{b}	1.59 ^{a}	1.51 ^{a}	1.50 ^{a}	1.61 ^{b}	1.91 ^{a}	1.85 ^{a}	1.79 ^{a}	1.50 ^{b}	1.68 ^{a}	1.59 ^{a}
Ca ($g \cdot kg^{-1}$)	0.87 ^{a}	0.82 ^{a}	0.86 ^{a}	0.85 ^{a}	0.61 ^{a}	0.65 ^{a}	0.67 ^{a}	0.64 ^{b}	0.74 ^{b}	0.76 ^{a}	0.75 ^{a}
Na ($g \cdot kg^{-1}$)	0.21 ^{a}	0.22 ^{a}	0.16 ^{b}	0.20 ^{a}	0.18 ^{a}	0.17 ^{a}	0.14 ^{b}	0.16 ^{a}	0.20 ^{a}	0.15 ^{b}	0.17 ^{b}

* Letter indicators at averages determine the so-called homogeneous groups (statistically homogeneous). The occurrence of the same letter pointer at averages (at least one) means that there is no statistically significant difference between them.

The geographical location of the places where JA was grown determined most of the chemical composition of the tubers. Significantly higher amounts of inulin, crude fiber, crude protein, endogenous amino acids, and magnesium were produced by the cultivars tested in Poland. On the other hand, tubers grown in Lithuania were characterized by a higher content of crude fat, true protein, total amino acids, essential amino acids, and nitrogen, phosphorus, potassium, calcium, and sodium. The content of exogenous amino acids did not depend on the geographic location (Table 4).

Individual cultivars showed a different reaction to geographic location (Table 4). The 'Albik' cultivar showed a higher content of crude protein, true protein, and calcium in Lithuania (Akademija), while in Poland (Parczew), this cultivar was characterized by a higher content of inulin and crude fiber, in the dry weight of tubers. The 'Rubik' cultivar obtained better results in the case of most quality features, such as the content of inulin, crude fiber, crude and proper protein, in the conditions of Parczew (Poland) (Table 4).

JA varieties cultivated in a more humid but cooler climate of Lithuania were characterized by a higher proportion of true protein in crude protein than in Poland, where periods of drought were frequent. The difference in the proportions of crude protein to true protein was 22.4% and 24.2% for the 'Albik' and 'Rubik' cultivars, respectively (Figure 6).

Soil and climatic conditions had a significant impact on all the tested tuber quality traits in the years of research (Table 5). In 2015 (optimal in terms of rainfall and a warm year characterized by dry periods in Poland), *H. tuberosus* tubers produced the most dry matter, soluble dry matter, inulin, crude and proper protein, sum of amino acids, endogenous and exogenous amino acids, ascorbic acid and nitrogen, phosphorus, potassium, and sodium. Homogeneous results in 2017 (with the highest rainfall) were obtained for dry matter, inulin, of ascorbic acid, nitrogen, phosphorus, and potassium. The largest amounts of crude fiber and crude fat were produced by tubers in 2016, the year with the lowest rainfall during the growing season. Homogeneous results in this respect were obtained in the last year of the study.

3.4. Variabilities of Chemical Composition Characteristics of Tubers

The highest coefficient of variation V, which is independent of the scale of units, was recorded for the content of the crude fibre, and the smallest was the content of vitamin C (Table 6). The kurtosis, as a measure of the concentration of results around the central value, is a measure of the shape of the distribution of results. If the value of this statistic is greater than zero, then the data exhibit a leptokurtic (slender) distribution. If kurtosis is less than zero, the distribution is a platykurtic (flattened) distribution. Our data indicated many extreme results (very high and very low with few results close to the average). Skewness (slant) determines the asymmetry of the distribution of the analysed variables, and in addition to kurtosis, it is a measure of the shape of the distribution of results. It informs us how the results of a given characteristic are shaped around the average. The coefficient of skewness for the normal distribution assumes the value "0" and indicates no asymmetry of the distribution, i.e., the distribution is perfectly symmetrical. In the case of crude fibre, crude fat, protein proper, nitrogen, phosphorus, potassium, and magnesium, the slant coefficient was above "0", which indicates that the distribution was right (positive) (Table 6).

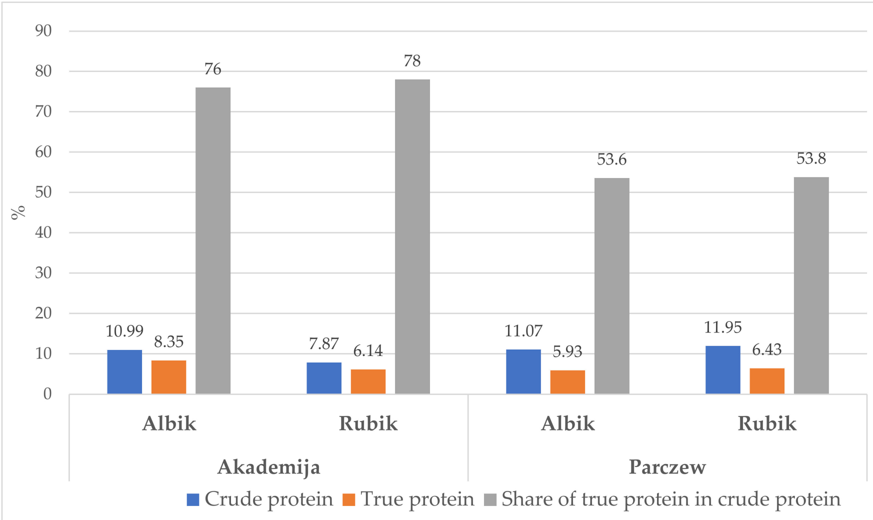

Figure 6. The content of crude and proper protein and the share of proper protein in crude protein, depending on the cultivars *H. tuberosus* and geographical locality.

The habitat conditions during the study period were mainly factors that primarily determined the variation in the chemical compositions of *H. tuberosus* tubers (18.5–54.9%) (Table 7). According to the results, another important source of variation was the interaction of the cultivars and years (21.0%), followed by cultivars (13.0%) and years × location (12.1%). Cultivars were the third source of variation due to the importance of the factor. Cultivar features had an average share of 12.6% in shaping the nutritional value of the tubers; this value ranged from 0.9 to 29.5%. The trait which was least dependent on the cultivar turned out to be the content of total protein, and the most—the content of sodium. The double interaction of geographic locality × cultivars was fifth in ranking of the percentage share of variation sources in phenotypic variability (8.8% on average); and ranged from 1.2%—in the case of crude fibre to 23.2%—in the case of sodium content in tubers. Finally, the fifth-largest share was research location (5.6%). The geographic origin of the cultivars was significant for the chemical characteristics of *H. tuberosus* tubers, except for the content of dry matter, protein and crude fibre, phosphorus, and magnesium. The share of this source of variability in phenotypic variability ranged from 0.5% (crude fibre) to 15.2%—in the case of inulin. The latter result is important for food processing as it indicates a location for inulin production plants.

Triple interactions ranked last in the ranking of the volatility of sources and constituted 4.9% of the phenotypic variability. A large share of the total volatility was the interaction between cultivars and research years, and its share ranged from 2.33% to 35.78% (Table 8).

Table 6. Descriptive statistics of chemical components of tubers.

Specification	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}
Mean	21.35	18.88	17.16	4.54	0.20	10.45	6.71	47.57	26.98	20.56	5.51	11.34	3.35	30.08	1.65	0.75	0.17
Median	22.06	18.88	17.93	4.45	0.20	10.98	6.31	47.57	26.98	20.56	5.52	11.34	3.35	29.34	1.60	0.75	0.17
SD *	3.03	2.50	2.10	1.16	0.02	1.46	0.88	4.03	2.89	1.22	0.20	1.41	0.13	2.39	0.18	0.11	0.02
Kurtosis	1.30	−1.36	−0.52	−2.07	−0.52	−0.45	0.07	−1.18	−0.87	−1.62	−0.69	−1.09	−0.82	−0.50	−0.95	−2.42	4.25
Slant	−1.49	−0.04	−0.92	0.11	0.48	−0.93	1.18	−0.25	−0.42	−0.01	−0.07	0.00	0.14	0.83	0.61	−0.01	2.07
Range	8.79	6.78	5.80	2.79	0.07	4.08	2.42	10.89	8.05	3.02	0.61	4.05	0.40	6.83	0.50	0.23	0.08
Minimum	15.29	15.40	13.49	3.24	0.17	7.87	5.93	41.38	22.26	19.01	5.20	9.31	3.16	27.41	1.44	0.63	0.15
Maximum	24.08	22.18	19.29	6.03	0.24	11.95	8.35	52.27	30.31	22.03	5.81	13.36	3.56	34.24	1.94	0.86	0.23
V ** (%)	14.20	13.22	12.21	25.45	11.03	14.00	13.12	8.48	10.72	5.95	3.67	12.46	4.01	7.96	10.95	14.92	12.99

x_1—dry mass (%), x_2—soluble of dry mass (%); x_3—inulin (FM) (%); x_4—crude fibre (%); x_5—crude fat (%); x_6—total protein (%); x_7—true protein (DM) (%); x_8—total amino acids (DM) (g·kg^{-1}); x_9—endogenous amino acids (DM) (g·kg^{-1}); x_{10}—exogenous amino acids (g·kg^{-1}); x_{11}—ascorbic acid (FM) (mg·100 g^{-1}); x_{12}—N (g·kg^{-1}); x_{13}—P(DM) (g·kg^{-1}); x_{14}—K (DM) (g·kg^{-1}); x_{15}—Mg (DM) (g·kg^{-1}); x_{16}—Ca (DM) (g·kg^{-1}); x_{17}—Na (DM) (g·kg^{-1}); * standard deviations; ** coefficient variability.

Table 7. Effect of cultivars, locality, and years on the chemical composition of *H. tuberosus* tubers and their percent contribution to the total variance.

Specification	Significance of Effect							Percentage Contribution of the Variance to the Total Variance						
	Years	Cultivars	Locality	Years × Cultivars	Years × Locality	Locality × Cultivars	Years × Cultivars × Locality	Years	Cultivars	Locality	Years × Cultivars	Years × x Locality	Locality × Cultivars	Years × Cultivars × Locality
Dry mass (%)	**	**	ns	ns	**	**	ns	54.9	13.6	1.1	4.4	13.7	9.1	3.2
Soluble dry mass (%)	**	**	ns	**	**	*	*	36.9	17.7	2.1	15.7	11.5	8.8	7.3
Inulin (FM) (%)	**	**	**	**	**	*	ns	29.6	9.2	15.2	29.0	9.9	7.1	1.1
Crude fibre (%)	**	**	ns	ns	**	ns	*	51.2	12.3	0.5	14.8	12.3	1.2	8.1
Crude fat (%)	**	**	**	**	**	ns	*	54.2	6.4	7.1	14.2	9.2	4.1	6.1
Crude protein (%)	**	ns	ns	**	**	**	ns	55.1	0.9	2.2	22.7	11.4	6.8	2.0
True protein (%)	**	**	*	**	ns	ns	*	18.5	29.5	5.8	31.5	1.1	3.5	12.1
Total amino acids (g·kg^{-1})	**	**	*	**	**	**	ns	31.1	13.2	2.1	25.8	17.7	9.8	0.9
Endogenous amino acids (g·kg^{-1})	**	**	*	**	**	**	ns	27.9	15.2	9.0	34.2	9.0	4.1	2.1
Exogenous amino acids (g·kg^{-1})	**	**	ns	**	**	**	ns	34.6	19.1	1.0	27.2	11.1	6.5	0.9
Ascorbic acid (FM) (mg·100 g^{-1})	**	**	ns	**	**	**	*	24.6	12.4	1.8	34.2	9.7	13.5	5.0
N (g·kg^{-1})	**	**	**	ns	**	**	*	34.2	11.9	12.1	2.3	23.4	11.1	5.0
P (g·kg^{-1})	**	**	ns	**	**	**	*	33.6	17.5	2.0	21.6	9.0	12.1	4.4
K (g·kg^{-1})	**	**	**	**	**	*	ns	35.9	12.7	9.9	18.7	11.8	9.9	1.2
Mg (g·kg^{-1})	**	*	ns	**	**	**	**	29.5	9.2	1.8	17.1	21.1	11.4	10.3
Ca (g·kg^{-1})	**	ns	**	**	**	*	ns	27.3	7.9	12.1	23.4	21.7	7.2	1.4
Na (g·kg^{-1})	**	**	*	**	ns	**	**	23.5	21.1	8.8	11.2	1.7	23.2	12.1
Average								35.4	13.0	5.6	21.0	12.1	8.8	4.9

** significant at $p = _{0.01}$, * significant at $p = _{0.05}$; ns—not significant at $p = _{0.05}$.

Table 8. Simple correlation coefficients.

	y1	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	x13	x14	x15	x16	x17
y_1	1.00																	
x_1	−0.43	1.00																
x_2	0.04	0.34	1.00															
x_3	0.78	−0.12	0.62	1.00														
x_4	0.97	−0.42	0.01	0.79	1.00													
x_5	−0.64	0.00	−0.79	−0.95	−0.60	1.00												
x_6	0.76	−0.18	0.43	0.94	0.85	−0.81	1.00											
x_7	−0.63	0.46	0.50	−0.06	−0.48	0.00	0.02	1.00										
x_8	0.23	0.25	0.98	0.76	0.20	−0.90	0.57	0.35	1.00									
x_9	0.32	0.20	0.96	0.82	0.30	−0.93	0.65	0.31	0.99	1.00								
x_{10}	0.04	0.34	0.99	0.59	−0.02	−0.78	0.37	0.43	0.97	0.94	1.00							
x_{11}	0.57	0.05	0.83	0.90	0.50	−0.99	0.70	0.00	0.93	0.95	0.84	1.00						
x_{12}	−0.85	0.55	0.49	−0.37	−0.86	0.14	−0.48	0.75	0.31	0.22	0.50	−0.04	1.00					
x_{13}	−0.49	0.52	0.85	0.11	−0.52	−0.35	−0.07	0.70	0.73	0.66	0.86	0.44	0.88	1.00				
x_{14}	−0.75	0.55	0.61	−0.18	−0.71	−0.01	−0.24	0.90	0.44	0.37	0.59	0.07	0.96	0.90	1.00			
x_{15}	0.84	−0.52	−0.42	0.45	0.90	−0.20	0.61	−0.60	−0.25	−0.14	−0.45	0.07	−0.98	−0.83	−0.88	1.00		
x_{16}	−1.00	0.42	−0.06	−0.78	−0.95	0.65	−0.74	0.65	−0.25	−0.34	−0.06	−0.59	0.83	0.46	0.75	−0.82	1.00	
x_{17}	−0.59	0.39	0.37	−0.19	−0.53	0.08	−0.19	0.70	0.24	0.19	0.34	−0.05	0.69	0.60	0.73	−0.61	0.60	1.00

y_1—locality; x_1—dry mass (%); x_2—soluble dry mass (%); x_3—Inulin (FM) (%); x_4—Crude fibre (%); x_5—Crude fat (%); x_6—crude protein (%); x_7—true protein (%), x_8—total amino acids (g·kg^{-1}); x_9—endogenous amino acids (g·kg^{-1}); x_{10}—exogenous amino acids (g·kg^{-1}); x_{11}—Ascorbic acid (FM) (mg·100 g^{-1}); x_{12}—N (g·kg^{-1}); x_{13}—P (g·kg^{-1}); x_{14}—K (g·kg^{-1}); x_{15}—Mg (g·kg^{-1}); x_{16}—Ca (g·kg^{-1}); x_{17}—Na (g·kg^{-1}).

The simple correlation coefficients show the overlapping relationships between the various characteristics of the chemical composition of tubers and geographic location and indicate the internal inter-reactivities between different elements of the chemical composition of *H. tuberosus* tubers (Table 8).

The highest positive correlation was found between the geographical location (location) and the content of crude fibre in *H. tuberosus* tubers (r = 0.97). A high positive correlation was also found for inulin (r = 0.78), crude protein (r = 0.76), ascorbic acid (r = 0.57), and magnesium (r = 0.84). A significant negative correlation between the chemical composition and location was found for crude fat (r = −0.64), true protein (r = −0.63), nitrogen content (r = −0.85), potassium (r = −0.75), calcium (r = −1.0), and sodium (r = −0.59) (Table 8). Pearson's correlation coefficient is called a standardized measure, which means that it is an easy-to-interpret measure. The correlation coefficient ranges from −1 (perfect negative correlation) through 0 (complete data independence) to 1 (perfect positive correlation). The values +1 and −1 for the correlation coefficient indicate perfectly related data. In this case, there is no room for chance, and it means a direct dependence of one value on another. Such a relationship has some direct cause-effect relationship and can be represented by a linear function.

4. Discussion

The quality of JA tubers is primarily related to their chemical composition. Dry substance content is the most important feature of the chemical composition of *H. tuberosus* tubers. Its amount turned out to be dependent on the genetic characteristics of the cultivars and weather conditions in the years of research, as well as on the interaction of these factors. The share of cultivars in shaping the quality of tubers ranged from 0.9 to 29.5%, with an average of 13.0%, which is less than 1/5 of the total phenotypic variation. In a study by Sawicka and Kalembasa [35] on the mineral composition of JA tubers, Sawicka et al. [3] confirmed this result. The majority of studies on the genetic traits quality of *H. tuberosus* and its components comes from analyses of combining ability. Evaluations of the Significance of the General Combining Ability (GCA) and the Specific Combining Ability (SCA) occur the most frequently. However, the proportion of GCA in genetic variability is usually higher [36,37]. Nevertheless, what limits this usefulness is the fact that they give information on genetic variability only in the specified genotype group. Therefore, more universal evaluation methods of JA quality characteristics are still being looked for. The high dry matter and inulin potential of *H. tuberosus* cultivars are mainly due to the fact that JA binds carbon dioxide through the Calvin cycle and thus has a C3 metabolic pathway for carbon binding through photosynthesis. The photochemical efficiency of this species is higher than that of many C3 species and is comparable to that of some C4 species [7,10]. The vitality of leaves, especially the late varieties, to which both of the studied cultivars belong, is longer, which leads to higher photochemical products and higher yields of dry matter of JA [9,10].

In addition to genetic variation, there is also environmental variation ($\sigma_L{}^2$), defined as condition-induced variability in the years of the study. The reasons for this variability are: the quality of the propagation material (seed potatoes), the heterogeneity of soil conditions (moisture, physicochemical properties of the soil, pH, soil enzymatic activity, humus content, nutrient abundance), diversified influence of the meteorological conditions (rainfall, air humidity and temperature, air pressure atmospheric), wind direction and speed, light intensity and duration, number of red light (R) to far red light (FR) quantum, photoperiodicity, weather anomalies such as: hurricanes, eddies, heat waves, hydrological drought, physiological drought; gravity, magnetism, ionizing radiation, and cosmic rays [38,39]. In addition, elements of inanimate nature are part of the environmental variability (physiographic conditions: exposure, exposure) characteristic of a given environment, which affect the organisms living in it, and at the same time are influenced by them. Too large fluctuations in, for example, air temperature and humidity, or the chemical composition of water and soil limit the development of plants, and the variability of these factors is often the result of human economic activity [40,41]. The light factor especially influences the induction of tuberization [42] and plant metabolism (assimilation, transpiration) [38,41,43]. The percent contribution to the total variance of individual traits and their interactions demonstrated that years was the factor that primarily determined the variation in the chemical compositions of *H. tuberosus* tubers (18.5–54.9%). Sawicka and Michałek [43] and Živčák et al. [44] showed that a metabolic process, which is particularly sensitive to many stress factors, is photosynthesis because photosynthetic dyes absorbed too much PAR energy in relation to the possibility of its transformation into chemical energy in the process of photosynthesis. The effects of photoinhibition of the photosynthetic apparatus are reflected in changes in chlorophyll fluorescence parameters [43].

The cultivar × years interaction exhibited quite a high share in the shaping of the quality of JA tubers, which constituted an average of 21.1%. Paungbut et al. [45], Skiba [46], and Lakić et al. [47] demonstrated a similar role of this interaction in the shaping of tuber quality. According to Bhandari et al. [37], a major cause of differences between genotypes or cultivars is the expression of a given characteristic in response to changeable environmental conditions. Research by Luis et al. [48] and Ma et al. [49] also point to the high variability of the above characteristics in research years. Sawicka et al. [3], when examining the variability of the characteristics of eighteen potato cultivars, attributed as much as 57.9–75.8% of the variability to the interaction of cultivar × years. According to Bhandari et al. [37], the main cause of differences between genotypes or cultivars is the expression of a given trait in response to changing environmental conditions. The research of Rymuza [40] and Pszczółkowski and Sawicka [39] also indicate a high variability of the above characteristics over the years of study. According to Bhandari et al. [37], the main cause of differences between genotypes or cultivars is the expression of a given trait in response to changing environmental conditions.

Geographical location had a low share in shaping the quality of *H. tuberosus* tubers (average 5.6%), which reflects the resistance of this species to unfavorable edaphic and biological conditions [5,50]. Lakić et al. [47] examined the variability of various local ecotypes of JA and estimated that the heritability of broad significance ranged from 34.66% (plant height) to 50.99% (dry matter yield/plant). Cieślik et al. [51] and Qiu et al. [6] found that the fresh mass of *H. tuberosus* tubers contained approximately 75 to 79% water and 13.5 to 18.5% carbohydrates. The tubers of both studied genotypes are suitable for obtaining inulin. Studies by Danilčenko et al. (2017) show that JA tubers contain 20.4–31.9% of dry weight, and their main components constituting 13–20% are monosaccharides, disaccharides, polysaccharides, but most of all, inulin is the dominant polysaccharide. According to the data by Kays and Kultur [9], Kays and Nottingham [10], the carbohydrate content in fresh JA tubers is 13.8–20.7%. The yield of inulin from the 'Albik' genotype amounts to a maximum of 47.05% DM, and from the 'Rubik' cultivar 40.88% of the dry weight. Inulin obtained from both of these genotypes, in terms of inulin and inulides content (max. 86.35% DM), ash (2.28% DM), and color intensity is comparable to commercial chicory preparations [14].

Kays and Kultur [9], evaluating 190 cultivated forms from Georgia and the USA, showed that later maturing clones generated higher yields, while the carbohydrate content was not related to the maturity period. JA tubers were also rich in the inulin, protein, and macro- and micronutrients. The protein in the tubers contains almost all essential amino acids such as lysine, threonine, and tryptophan [3,35]. The studied chemical constituents of JA tubers were characterized by the highest stability of the ascorbic acid content, and the greatest variability of the crude fiber.

The cultivar 'Albik' was characterized by greater nutritional value than 'Rubik' both in Lithuanian and Polish soil and climatic conditions. Tubers from crops in Lithuania were characterized by lower content of inulin, crude fiber and protein, ascorbic acid, total and endogenous amino acids, but a higher true protein and macroelements contents. Similar results were obtained by Danilčenko et al. [8] and Lakić et al. [47].

The tuber protein contained almost all the essential amino acids, such as lysine, threonine and tryptophan, as confirmed by Cieślik et al. [51] Sawicka [5], and Sawicka et al. [3]. Ascorbic acid content exhibited the highest stability among the studied chemical constituents of JA tubers, and crude fibre exhibited the greatest variability. The cultivar 'Albik' was characterized by greater nutritional value than 'Rubik' in Lithuanian and Polish soil and climatic conditions. Tubers from crops in Lithuania were characterized by lower contents of inulin, crude fibre and protein, ascorbic acid, and total and endogenous amino acids, but higher true protein and macro- and microelement contents. Similar results were obtained by Danilčenko et al. [2,3,8].

The main reason for the recognition of JA tubers as a functional, probiotic food is the high content of fructans, which was confirmed by Cieślik et al. [51,52] and Sawicka [5]. The high accumulation in dry matter tubers is generally accompanied by an accumulation of inulin and soluble dry matter [6,51]. The protein content of JA tubers ranged from 2.5% to 3.4% (FW) (7.87–11.95% in dry mass of tubers). Danilčenko et al. [53], Ma et al. [49], and Sawicka and Kalembasa [54] showed that tubers contained protein 2–3%. and all of the essential amino acids in appropriate proportions that are almost ideal for humans. These components are an important part of enzymes and participate in cellular metabolism and the accumulation and dissimilation of organic substances [8,51,53].

Assessment of the influence of varietal features and meteorological conditions in two different geographical locations confirmed the possibility of obtaining a higher quality crop with large amounts of biologically active compounds in JA tubers, which will allow growers and consumers to choose the most appropriate cultivars with a tendency to accumulate the most biologically valuable compounds.

Practical meaning of research: The results of the research contribute to confirming the method of supplementing scientific knowledge, formulating opinions on the change in the chemical composition of the JA during the growing season. Analyzed amounts of proteins, carbohydrates, inulin, vitamin C, fiber and crude fat, and macronutrients are antioxidants in JA as in the stages of its organogenesis [7].

H. tuberosus tubers are characterized by a high content of alkaline-forming minerals. The level of elements such as potassium and calcium in tubers of this species is higher than in potato tubers, carrots, sugar beet roots, peppers, onions, or apples [7,51,52]. They contain from 43.7 to 51.2 $g \cdot kg^{-1}$ of minerals such as: potassium, phosphorus, magnesium, calcium, sodium, chlorine, manganese, copper, zinc, iron, iodine, and others [5]. The ash composition of the underground parts of JA is comparable to the composition of potato tubers. Cieślik et al. [51] noted three times higher iron content in *H. tuberosus* tubers. However, this is contradicted by the research by Skiba [46], where the level of this element in tubers was almost two times lower than in potatoes. Small tubers are more ash rich than large ones. Comparable amounts of ash were found in tubers of this species harvested in autumn (50 $g \cdot kg^{-1}$ DM) and spring (51 $g \cdot kg^{-1}$ DM) [52].

Tubers of this species are particularly rich in potassium. This macroelement influences the ionic and water balance of the organism [3]. In the cytoplasm of plant cells, potassium acts as an activator of about 80 enzymes and balances the negative charge of many inorganic and organic anions. In cell juice, it acts as an accompanying cation in the transport of nitrates and sugars, and regulates cell turgor, which indirectly, in the case of the cells of the stomata, influences the entire process of gas exchange of plant leaves. Protein synthesis in cellular ribosomes also requires high concentrations of potassium. Disorders of this process lead to the accumulation of soluble nitrogen compounds in the form of nitrates and amines in plants, including the toxic putrescine [46]. There are also other important functions of potassium, such as maintaining cation-anionic balance, best loading/unloading, transporting, and assimilating minerals [4,28]. Potassium maintains the turbulence of plant cells; hence, it is important in periods of drought, during the growing season—it increases the leaf surface and the content of chlorophyll in them, delays the aging of the leaves, and contributes to greater photosynthesis of the canopy. In addition, it increases the resistance of *H. tuberosus* plants to lodging and disease, stimulates root formation, reducing water loss, reduces environmental stresses caused by temperature, humidity, transpiration and respiration, wind, and salinity conditions. It also protects plants against drought and frost. Potassium deficiency may be one of the causes of early flowering, because the growth of cambium in the stems of JA is reduced [4]. Danilčenko et al. [2] obtained potassium content at the level of 31.9 g·kg^{-1} DM of tubers; Sawicka and Kalembasa [54] obtained a slightly higher content of this element in tubers, but under the conditions of high mineral fertilization. According to USDA (2018) data, its amount in raw tubers is on average 41.7 g·kg^{-1} and changes during culinary processing. Potassium losses during cooking reach up to 33%, but do not occur during baking [10,51]. In the conducted studies, the average potassium content was obtained at the level of 30.08 g·kg^{-1} DM. The factor determining the content of this element in tubers to the greatest extent was the meteorological conditions in the years of the study, which were decisive in 35.9%, cultivars determined 12.7%, and location 9.9% of the total variability. The remaining part of phenotypic variability was shaped by cooperation of the localization with cultivars.

An important component of ash is nitrogen. The content of this element ranges from 10.21 to 22.53 g·kg^{-1} DM [2]. In the conducted research, the average was obtained—11.34 g·kg^{-1} DM of tubers. Nitrogen is a component the amount of which largely depends on the applied organic and mineral fertilization [54]. This component is the main factor of yielding; moreover, it is a component of proteins, as well as harmful nitrates and nitrites [54–56]. Environmental factors influenced 34.2%, geographical location 12.1%, and cultivars 11.9%, the phenotypic variability of this trait. The rest of the phenotypic variability was attributable to the interaction of cultivars and locations with the years of research.

Phosphorus was present in JA tubers in the amount from 3.22 to 3.60 g·kg^{-1} DM, depending on the location, cultivar, and year of research. According to USDA [57], the phosphorus content in tubers is on average at the level of 7.8 g·kg^{-1} DM. Phosphorus, like nitrogen, is involved in all life processes in plants, and is essential for the proper course of photosynthesis, respiration, metabolism, and especially for the formation of proteins and reserve substances [5,46]. Its nonelection causes serious disturbances in the basic life functions of plants, which results in the weakening of the development and functioning of individual organs, especially the root system. This element is critical in balancing nutritional needs. The plants well fed with it are more resistant to stress, less susceptible to diseases, and have better yields; they also tolerate low temperatures better, show greater tolerance to water shortages and low soil pH [54,55,58]. The phosphorus content of JA tubers was quite high and amounted an average of 3.35 g·kg^{-1} DM. The 'Albik' cultivar was more abundant in this element than the 'Rubik' cultivar. The content of phosphorus was modified to the greatest extent by the conditions in the study years—33.6%, 17.5% by cultivars, and the location of the studies did not have a significant impact on this value (2.0%). The remaining sources of variation concerned the interaction of experience factors, but the interaction of years' × cultivars had the largest share in the phenotypic variability of this trait—21.6%.

A very important component, especially for JA, is calcium, but not only is this element important, but also the ratio of its activity in the soil solution to the total activity in the soil solution of Ca, Mg, and K. Calcium taken from the soil solution is transported to a part aboveground xylem. On the other hand, transport over short distances involves numerous transport proteins, the so-called channels, pumps, and ionic carriers [4,43]. It is an element which does not move in the plant in the phloem, meaning that its deficiency cannot be supplemented by redistribution from older to younger leaves or from leaves to developing tubers [4,31]. Calcium deficiency causes deformation of young leaves, dieback of apical and flower buds, as well as root growth cones, because calcium moves very poorly in the plant. In addition, it causes many physiological diseases. Therefore, an important issue is the constant presence of easily digestible calcium in the zone of the root system [54]. In production plantations of JA, the role of calcium is particularly important, as this element determines the balance of nutrients in food and feed [4]. Calcium is one of the basic nutrients of plants. It plays both a structural role and functions as a universal information transmitter. It is involved in numerous processes, from cell divisions to response to a wide range of internal and external factors, playing a role from mediator to stimulator of response [43]. Calcium has a great influence on the condition of colloids because it increases viscosity, reduces the hydrophilicity of the cytoplasm, thus affecting the permeability of cell membranes. The calcium in JA tubers ranged from 0.63 to 0.85 $g \cdot kg^{-1}$ DM, depending on the cultivar, location, and weather conditions in the years of the research. According to USDA [57], the concentration of calcium in tubers is on average 1.4 $g \cdot kg^{-1}$ DM.

Magnesium is absorbed by *H. tuberosus* plants in large amounts. It is the central chlorophyll atom, determining the color of the leaves and the course of metabolism, and affecting the solubility of phosphorus in the soil. As a result of its deficiency, the tissue between veins turns yellow (the so-called interveinal chlorosis), and over time, this tissue dies, which leads to inhibition of growth or even drying of whole plants [28,54]. Magnesium deficiency is first observed on older leaves due to the easy movement of magnesium in the phloem, i.e., redistribution from older to younger leaves or from leaves to developing tubers [46]. The ratio of potassium to magnesium is important in the photosynthesis process, as it affects the opening of the stomata, which is associated with proper gas exchange and photosynthesis efficiency. The antagonistic effect of potassium in relation to magnesium causes the disappearance of its available forms in soil [54]. In the experiment, the magnesium content was obtained at the level of 1.65 $g \cdot kg^{-1}$ DM; only cultivars and conditions in the years of research and their interaction significantly influenced the content of this macronutrient. Research location did not have a significant impact on this trait (2.0% share in phenotypic variability).

The sodium content in *H. tuberosus* tubers was at the level of (0.14–0.21 $g \cdot kg^{-1}$ DM of tubers). A similar amount of this element in tubers was found by Kays and Nottingham [10] and Rossini et al. [55]; a much higher content was found by Cieślik et al. [52]—the author noted a higher content of it in tubers harvested in spring than tubers harvested in autumn. Sawicka and Kalembasa [35] consider this element beneficial for plants as it can replace potassium.

Obtaining tubers with an appropriate chemical composition and consumption quality depends not only on the cultivar and weather conditions, but also on edaphic factors, which are soil factors that determine the growth and development of cultivated plants, namely soil structure, soil density, nutrient richness, oxygen content and water in the soil, the amount of humus, the pH level, the amount and activity of microorganisms (bacteria, fungi, yeasts) and soil enzymes, and thus the specific composition of soil-dwelling organisms [4,39]. The management of cultivation practices should be adapted to both the weather conditions and the requirements of the plants. Timely cultivation and care treatments also play an important role, as they also depend on weather conditions. One of the elements of agricultural engineering is the proper density of plants per unit area, which can be expressed in the number of planted tubers, and their average weight and chemical composition are related to the number of stems and tubers under a bush [7,46]. The analysis of Pearson's simple correlation coefficients carried out in this study showed that the strongest positive relationship was between the geographical location and the crude fiber content in *H. tuberosus* tubers (r = 0.97). In addition, a very high positive correlation was found for magnesium (r = 0.84), inulin (r = 0.78), crude protein (r = 0.76), and ascorbic acid (r = 0.57). A significant, but negative correlation with research location was found for the content of calcium (r = −1.0), nitrogen (r = −0.85), and potassium (r = −0.85); crude fat (r = −0.64), crude protein (r = −0.63), and sodium (r = −0.59). Negative correlation can be interpreted that as the value of one feature increases, the value of the other one decreases. Balzarini et al. [41], Ahmed et al. [58], and Žaldarienė [7] demonstrated a significant influence of the interaction between the genotype and the environment (G $\times$ E) and a significant interaction between the studied strain and the place of growth.

The highest positive correlation was found between the geographical location and the content of crude fiber in *H. tuberosus* tubers (r = 0.97). A high positive correlation was also found for inulin (r = 0.78), crude protein (r = 0.76), ascorbic acid (r = 0.57), and magnesium (r = 0.84), while a significant negative correlation between the chemical composition and location was found for crude fat (r = -0.64), true protein (x = -0.63), nitrogen content (r = −0.85), potassium (r = −0.75), calcium (r = −1.0), and sodium (r = −0.59). This was confirmed by the results of Sawicka and Kalembasa [54,56].

The complex nature of the tested of JA cultivars required the use of multidimensional methods, since the comparative study carried out in regard to the many characteristics that were analyzed separately did not clarify sufficiently the complexity of this phenomenon. It did not make it possible to completely evaluate their qualitative diversification that were similar with regard to many characteristics at the same time. In the opinion of Crossa and Franko [31], Rymuza [40], and Bhandari et al. [37], a complex evaluation of cultivar diversification may be carried out while using at the same time multi-characteristic methods of their diversification. Therefore, future cultivar studies need to be carried out in the above direction. The high diversification of the studied cultivars, in regard to the analyzed quality characteristics, enables the selection of favorable genotypes that are useful in creative JA cultivation. The cultivars with the best morphological, economic, and quality characteristics; and the highest resistance to fungal diseases should be used in a breeding process to create JA genotypes with the desired traits.

The threat of global climate change reinforces the idea that JA is a highly productive crop with a relatively low input that provides the basis for feeding an increasing global population, while also providing renewable energy. This species may in the future ensure food and energy security for countries in the temperate zone.

5. Conclusions

Meteorological conditions and genetic traits of cultivars determined changes in the chemical composition of JAs during vegetation. The geographical location had the least impact on the quality of tubers tested, and the interaction between the location of the studies and cultivars and the interaction of location × years had the smallest share in the phenotypic variability of this species.

The JA tubers were rich in inulin, fibre, protein, and macro- and micronutrients. The amounts of macroelements, such as K, P, Mg, and Ca, were similar to those in potato tubers, and the sodium content was comparable with other root crops.

Among the studied chemical constituents of JA tubers, the ascorbic acid content exhibited the highest stability, and crude fibre exhibited the greatest variability.

The tubers from crops in Lithuania were characterized by a lower content of inulin, crude fibre, crude protein, ascorbic acid, and total endogenous amino acids, but higher true protein and macroelements contents, except for magnesium, than tubers in Poland.

A tendency to change the chemical composition of tubers was observed as *H. tuberosus* cultivation was moved from Central-Eastern Europe to the North-East of Europe.

The properties of the studied JA cultivars have an impact on the content of minerals, which can significantly improve the nutritional status of both humans and animals, and reduce their nutritional and health problems. Assessment of the influence of varietal characteristics, meteorological conditions, and geographic locations on the amount of biologically active compounds in JA will allow growers and consumers to choose the most suitable cultivars, with a tendency to accumulate most of the biologically valuable compounds.

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Abbreviations

C	carbon
Ca	calcium
Corg	organic carbon
DAP	days after planting
ES	The European Union
GCA	General Combining Ability
H. tuberosus	*Helianthus tuberosus*
JA	Jerusalem artichoke
K	potassium
Mg	magnesium
N	nitrogen
NPK	fertilizer mixture
P	phosphorus
P_2O_5	mobile phosphorus
pH	a measure of acidity or alkalinity
r	correlation coefficient
SCA	the Specific Combining Ability
SCN	standard climatic norm
SHC	Sielyaninov Hydrothermal Coefficient

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