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ORIGINAL ARTICLE

Protein and sugar content of tubers in potato plants treated with biostimulants

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Abstract

The use of biostimulants and cultivar selection play an important role in modern potato farming because they influence tuber yield and quality. The nutritional value and processing suitability of potato tubers are affected by their content of total protein, reducing sugars and sucrose. The aim of this study was to determine the effect of biostimulants on the content of total protein, glucose, fructose and sucrose in potato tubers (skin, flesh and whole tubers with skin), at harvest and after 5 months of storage. The experimental materials included tubers of five edible potato cultivars: Irga, Satina, Valfi, Blaue St. Galler and HB Red. During the growing season, potato plants were treated with the following biostimulants: Asahi SL, Bio-Algeen S-90, Kelpak SL and Trifender WP. Control plants were not treated with biostimulants. The total protein content of tubers was determined by the Kjeldahl method. Simple sugars and sucrose were determined by high-performance liquid chromatography. At harvest, total protein concentration was significantly higher in purple- and red-fleshed cultivars than in cream- and yellow-fleshed cultivars. An analysis of tuber parts revealed that flesh had the highest protein content. The total protein content of tubers increased during storage. Biostimulants had no significant effect on total protein concentration in tubers at harvest or after storage. The content of simple sugars and sucrose was higher in the skin, flesh and whole tubers of purple- and red-fleshed cultivars, than in cream- and yellow-fleshed cultivars. Potato tubers with colored flesh accumulated the highest amounts of total sugars. Biostimulants, in particular Bio-Algeen S-90 and Kelpak SL, contributed to the accumulation of monosaccharides and the disaccharide in potato tubers, and, in consequence, total sugars. Their concentrations in potato tubers increased during storage.

Keywords: biostimulants, reducing sugars, *Solanum tuberosum* L., sucrose, total protein

Introduction

Potato (*Solanum tuberosum* L.) is one of the major non-cereal food crops that is grown in more than 160 countries around the world. In recent years, the consumption of fresh potatoes has declined in favor of processed potato products (Ezekiel *et al.* 2013). Potatoes are widely cultivated because they are a rich source of nutrients important in the human diet. They contain 11–18.3% of starch (edible potatoes), 2% of protein (abundant in exogenous amino acids, comparable with soy protein), 2–2.5% of dietary fiber, sugars, vitamins (C, B1, B2, B6, PP), polyphenols, flavonoids, carotenoids, and minerals (K, Ca, Mg, P, J, Fe, Cu, Zn) (Wegener *et al.* 2015; Wierzbowska *et al.* 2016).

According to Divís *et al.* (2007), total protein content and average protein content on a dry matter basis were significantly higher in organically grown potato tubers than in potatoes from conventional farming systems. Bártová *et al.* (2013) found that organic potatoes contained significantly less nitrogen and nitrates than conventional potatoes, but the protein and patatin content of potatoes did not differ significantly between the compared farming systems. Rychcik *et al.* (2020) demonstrated that organic potatoes contained around 20% less nitrogen than potato tubers from integrated or conventional farming systems.

Sugars play a regulatory role by controlling plant growth and development in all stages of the plant life cycle (Stokes *et al.* 2013). Sugars act as signaling molecules that participate in defense responses to abiotic and biotic stress (Bolouri Moghaddam and Van den Eden 2012; Morkunas and Ratajczak 2014). Sugars are also an important component of potato tubers, determining their quality.

Cultivar selection and the application of biostimulants play an important role in modern potato cultivation. These factors affect potato yields and tuber quality, which are very important parameters in the production of potatoes for direct consumption and processing (Grudzińska 2012; Kołodziejczyk 2013; Pszczółkowski and Sawicka 2018). Potato cultivars with colored skin and flesh have higher nutritional value than cream- and yellow-fleshed cultivars, and their popularity has increased in recent years. Potatoes with colored flesh contain more phenolic compounds, including anthocyanins (Hamouz *et al.* 2010) which have antioxidant and antibacterial properties, and deliver health benefits (Lachman *et al.* 2012). Głosek-Sobieraj *et al.* (2019) found that potato cultivars with blue-purple- and red-colored flesh were more abundant in chlorogenic acids than cultivars with yellow- and cream-colored flesh, in particular after the application of Asahi SL and Trifender WP biostimulants.

Biostimulants are increasingly applied in sustainable and environmentally-friendly farming systems to improve nutrient use efficiency, enhance soil fertility, decrease fertilizer rates (mainly N fertilizers), increase agricultural productivity, yields and crop quality, and improve plant tolerance to adverse environmental conditions (Khan *et al.* 2009; Du Jardin 2015; Yakhin *et al.* 2017). Regulation (EU) 2019/1009 lays down the rules for the application of biostimulants in crop production. The main groups of biostimulants include seaweed extracts, humic substances, inorganic salts, chitin and chitosan derivatives, microbial biostimulants, free amino acids, and other nitrogen-containing substances (Calvo *et al.* 2014; Bulgari *et al.* 2015). Wierzbowska *et al.* (2015) found that Asahi SL, Bio-Algeen S-90, and Kelpak SL biostimulants increased tuber yields in very early and medium-early maturing potato cultivars. Kowalska (2016) demonstrated that microbial biostimulants applied to soil before tuber planting and four foliar biostimulant treatments significantly increased potato yields, including marketable yields. GreenOK-Universal Pro and Asahi SL biostimulants increased dry matter yield and starch yield in the production of early cultivars of edible potatoes (Baranowska and Mystkowska 2019). In a study by Głosek-Sobieraj *et al.* (2018), biostimulants (Bio-Algeen S-90, Kelpak SL, Trifender WP, and Asahi SL) significantly decreased the prevalence of *Phytophthora infestans* infections during the growing season and increased tuber yields in selected potato cultivars by increasing the percentage of medium-sized tubers. Seaweed extracts increased vitamin C concentrations in *Trigonella foenum-graecum* (Khemnar and Chaugule 2000). In the work of Zodape *et al.* (2011), foliar application of *Kappaphycus alvarezii* seaweed extract improved the quality of tomatoes by increasing the content of carbohydrates, vitamin C, and ions. In turn, Grabowska *et al.* (2015) reported a decrease in the content of soluble sugars, beta-carotene, and vitamin C, as well as a decrease in the total antioxidant activity of tomatoes treated with Asahi SL. In potato tubers, sugar content is an unstable parameter that is affected by storage conditions (Żołnowski 2010; Grudzińska 2012). Grudzińska *et al.* (2014) found that air temperature and precipitation levels between September 11th and 30th significantly influenced the content of reducing sugars in potato tubers. When air temperature dropped below 12°C in the analyzed period, the content of reducing sugars increased by around 0.6 mg · kg^{-1} fresh matter (FM) per every 1°C (under the investigated soil conditions).

The aim of this study was to determine the effect of biostimulants on the content of total protein, reducing sugars, sucrose and total sugars in potato tubers (skin, flesh and whole tubers with skin) of cream-, yellow-, purple- and red-fleshed cultivars, at harvest and after 5 months of storage.

Materials and Methods

Experimental materials, field experiment

Tubers of five edible potato cultivars were analyzed: one cultivar with cream-colored flesh – Irga (Poland), one cultivar with yellow-colored flesh – Satina (Germany), two cultivars with purple-colored flesh – Valfi (Czech Republic) and Blaue St. Galler (Switzerland), and one cultivar with red-colored flesh – Highland Burgundy Red (France and Great Britain). Potatoes were grown in a small-area microplot field experiment established in Tomaszkowo near Olsztyn, Poland (53°41'N, 20°24'E). In both years of the study, weather conditions in May – August were similar, with an average air temperature of 16.2°C and total precipitation of 200 mm and around 160 mm, respectively. Oat was the preceding crop. Seed potatoes were planted at the end of April, in heated soil (8–10°C), at a depth of 10 cm, 40 cm apart, with inter-row spacing of

67.5 cm. Agronomic practices were identical in all plots. Pathogens and pests were controlled chemically, and weeds were controlled mechanically. Biostimulants were applied at the doses recommended by the manufacturers, at 10–14-day intervals during the growing season (beginning in BBCH stage 39 – crop cover complete):

- 0.1% solution of Asahi SL (natural nitrophenols found in plants: ortho-nitrophenol, sodium para-nitrophenol, sodium 5-nitroguaiacol) – four foliar applications;
- 1.0% solution of Bio-Algeen S-90 (extract of *Ascophyllum nodosum* brown seaweeds that contains amino acids, vitamins, alginic acid and macronutrients: N – 0.2, P_2O_5 – 0.06, K_2O – 0.96, CaO – 3.1, MgO – 2.1 g · kg^{-1}, and micronutrients: B – 16.0, Fe – 6.3, Cu – 0.2, Mn – 0.6, Zn – 1.0 mg · kg^{-1}, and Mo, Se, Co) – four foliar applications;
- 0.2% solution of Kelpak SL (extract of *Ecklonia maxima* brown algae that contains 11 mg · dm^{-3} auxins and 0.031 mg · dm^{-3} cytokines) – seed potato coating and two foliar applications;
- Trifender WP (*Trichoderma asperellum* fungal spores at a concentration of 5×10^8 g^{-1} of the product, T1 isolate, NCAIM 68/2006) – soil application and four foliar applications.

Control plants were not treated with biostimulants.

Potato tubers were harvested at the end of August, and they were stored for 5 months at 5°C.

Preparation of plant material for chemical analysis

Potato tubers (35–50 mm) were randomly collected for analyses at harvest and after 5 months of storage at 5°C. The tubers were rinsed in water, and some of them were peeled (skin thickness of 3–4 mm). The plant material was divided into: skin – cut into 1 cm segments, tubers without skin, and whole tubers with skin cut into 1 × 1 × 1 cm cubes. The prepared material was freeze-dried in a Alpha 1-4 LDplus freeze dryer (Doncerv®) and ground in a laboratory mill (A 11 basic). The average dry matter (DM) content of tubers was 21.2–26.8% (unpublished data).

Total protein content

Plant material was mineralized in concentrated sulfuric acid at 480°C for 160 min (BUCHI Speed Digester K-439 – BUCHI Labortechnik AG, Switzerland). The total protein content of potato tubers (DM basis) was determined by the Kjeldahl method (KjelFlex K-360 distillation unit – BUCHI Labortechnik AG, Switzerland). The conversion factor of 6.25 was used to convert nitrogen content into protein content (Maclean *et al.* 2003).

Sugar content

The prepared material was extracted with a 50% aqueous solution of methanol. The sugar (glucose, fructose and sucrose) content of samples was determined after purification and filtration (0.20 μm) by high-performance liquid chromatography (Waters 2695 HPLC system with Waters 2414 refractive index detector and Bio-Rad Aminex HPX-87H column); mobile phase – 0.5 mM solution of H_2SO_4, flow rate – 0.6 ml · min^{-1}. Sugars were quantified by measuring the peak areas and retention times based on the relevant calibration curves (using an external standard method).

Statistical analysis

The results were processed statistically by analysis of variance (ANOVA). Statistical analyses were done with the Statistica® 13.3 (StatSoft, Tulsa, OK, USA). The significance of differences between group means was estimated by Tukey's post-hoc range test at a significance level of $p = 0.05$.

Results and Discussion

The total protein content of tubers (skin, flesh, whole tubers with skin) was higher in purple- and red-fleshed cultivars than in cream- and yellow-fleshed cultivars, and in flesh than in skin (except for cv. Satina in the Bio-Algeen S-90 treatment and cv. HB Red in control and Trifender WP treatments) and whole tubers (except for cv. HB Red in the Trifender WP treatment). The total protein content of flesh ranged from 77.1 to 83.5 g · kg^{-1} DM in cream- and yellow-fleshed cultivars (cv. Satina in control and Trifender WP treatments, respectively), and from 78.4 (cv. HB Red in the Trifender WP treatment) to around 92 g · kg^{-1} DM (cv. Blaue St. Galler in Asahi SL and Bio-Algeen S-90 treatments) in red- and purple-fleshed cultivars (Table 1). Unlike biostimulants, cultivars affected the total protein content of freshly harvested tubers. In comparison to cvs. Irga and Satina, protein content was significantly higher in the skin of cvs. Blaue St. Galler and HB Red, in the flesh of cvs. Valfi and Blaue St. Galler, and in whole tubers with skin in all cultivars with colored flesh (Fig. 1). No differences in the total protein content of whole tubers or their parts were found between biostimulant treatments and the control treatment (Fig. 1). In a study by Arafa *et al.* (2012), foliar application of seaweed extract (*Ascophyllum nodosum)* increased the crude protein content of potato tubers from 10.94% to 14.9%, compared to the control treatment. The cited authors found that biostimulant application combined with soil fertilization with potassium at 40 kg · ha^{-1}

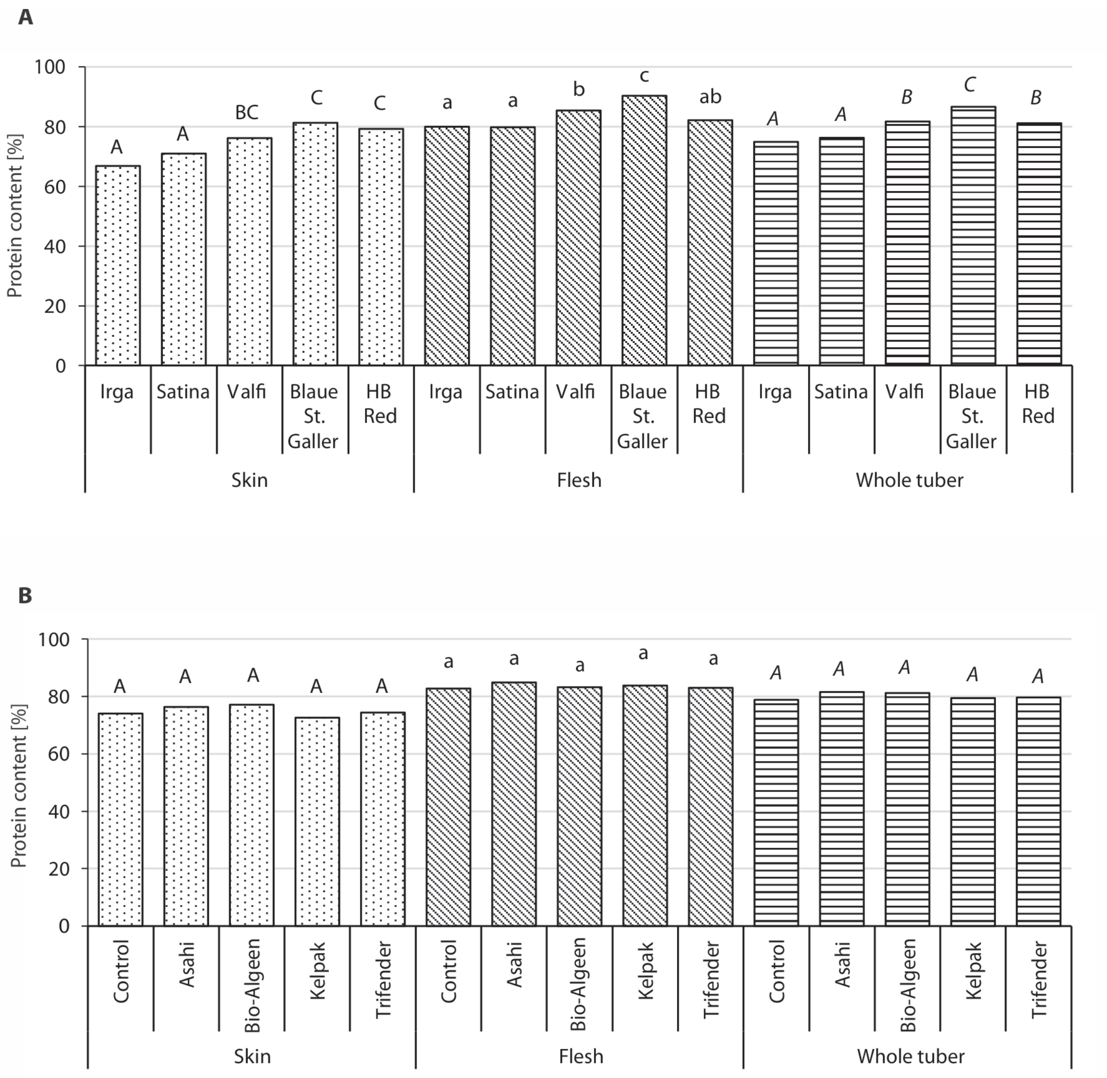

Fig. 1. Effects of cultivar (A) and biostimulant (B) on the total protein content of potato tubers.
Values followed by the same letters do not differ significantly in Tukey's (HSD) test ($p < 0.05$). Capital letters – skin, small letters – flesh, italic letters – whole tubers

K_2O induced a further increase in the protein content of tubers. Haider *et al.* (2012) demonstrated that foliar application of seaweed (*A. nodosum*) extract "Primo" increased the nitrogen and protein content of potato tubers, whereas Al-Bayati and Al-Quraishi (2019) reported that the protein content of potato tubers decreased in response to *A. nodosum* extract. According to Zodape *et al.* (2011), foliar application of seaweed extract (*K. alvarezii*) increased tomato yields and the protein content of fruit. In a Polish study by Wierzbowska *et al.* (2015), *E. maxima* extract (Kelpak SL) had no effect on the total nitrogen content of potato tubers. Mystkowska (2018) noted a minor increase in the content of total and crude protein in tubers of potato cvs. Honorata, Jelly and Tajfun treated with Kelpak SL, relative to the control treatment. Kalinowski *et al.* (2018) found that the protein content of tubers in very early potato cultivars was significantly affected by genotype. In turn, the Tytanit® biostimulant did not modify the protein content of potato tubers after harvest. Wadas and Dziugiel (2020) reported that biostimulants had no influence on the protein content of potato tubers, but the nitrate content of tubers was 8.50 mg · kg^{-1} lower in cv. Denar treated with Kelpak SL and HumiPlant.

The total protein content of all tuber parts increased during storage, and cultivar had no significant effect on this parameter. The greatest increase in protein content was noted in skin (maximum of 13.3% in cv. Satina). In flesh and whole tubers, protein content increased by a maximum value of 5.5% in cv. Irga and around 6.2% in cvs. Satina and HB Red. Biostimulants had no significant effect on changes in the total protein content of skin (protein content increased, except in the Bio-Algeen S-90 treatment) and whole tubers during storage. An increase in the total protein content of flesh under

Table 1. Protein content of potato tubers [g · kg^{-1} DM]

Cultivar	Biostimulant	Skin	Flesh	Whole tuber
Irga	Control	64.28 a	80.07 ab	74.30 abc
	Asahi SL	71.21 abc	81.57 abc	77.96 b-e
	Bio-Algeen S-90	65.93 ab	78.68 ab	74.05 abc
	Kelpak SL	64.95 a	81.20 abc	74.18 abc
	Trifender WP	67.66 abc	78.14 ab	73.85 ab
Satina	Control	64.79 a	77.12 a	69.92 a
	Asahi	71.64 abc	81.27 abc	77.55 b-e
	BioAlg	82.20 abc	78.98 ab	81.18 c-g
	Kelpak	72.01 abc	77.95 ab	76.13 a-d
	Trifend	64.02 a	83.48 abc	76.33 a-d
Valfi	Control	74.76 abc	85.99 abc	81.01 b-f
	Asahi	79.72 abc	86.03 abc	83.60 e-h
	BioAlg	76.00 abc	82.76 abc	80.25 b-f
	Kelpak	74.79 abc	86.63 abc	82.54 d-h
	Trifend	75.40 abc	85.47 abc	81.07 b-g
Blaue St. Galler	Control	81.72 abc	89.82 bc	86.52 fgh
	Asahi	83.38 bc	92.33 c	88.24 gh
	BioAlg	84.45 c	92.12 c	89.18 h
	Kelpak	75.46 abc	87.81 abc	82.98 d-h
	Trifend	81.23 abc	89.43 bc	86.18 fgh
HB Red	Control	84.54 c	80.58 abc	82.28 d-h
	Asahi	75.61 abc	83.03 abc	80.29 b-f
	BioAlg	76.86 abc	83.42 abc	81.17 c-g
	Kelpak	75.62 abc	85.19 abc	81.19 c-g
	Trifend	83.46 bc	78.39 ab	80.68 b-f

Values followed by the same letters in columns do not differ significantly at $p \leq 0.05$

the influence of biostimulants was significantly lower (except for Bio-Algeen S-90) than in the control treatment (Fig. 2). However, Černá and Kráčmar (2010) demonstrated that the concentrations of most amino acids and total protein in potato tubers decreased during storage. Another study (Pęksa *et al.* 2018) revealed that the content of nitrogen compounds and amino acids decreased during storage (3 and 6 months at 2°C and 5°C) in tubers of six potato cultivars with purple, red and yellow flesh, and the noted decrease was affected by storage time and cultivar. The content of total protein and, in particular, amino acids decreased with prolonged storage. Tubers stored at 2°C had higher amino acid content than those stored at 5°C.

The quality of edible potatoes, especially those intended for direct consumption or processing, is affected by the content of sugars, including reducing sugars (glucose and fructose) and sucrose. The content of total sugars and reducing sugars exceeding 1% and 0.5% (on a fresh matter basis), respectively, is responsible for the sweet flavor of potatoes (Leszczyński 2000). According to Nowacki (2020), the optimal (maximum) content of reducing sugars in potato tubers is as follows: up to 5 g · kg^{-1} FM – direct consumption, pickled potatoes, chips; up to 2.5 g · kg^{-1} FM – dried potatoes; up to 1.5 g · kg^{-1} FM – crisps. At high temperatures, reducing sugars participate in the formation of harmful acrylamide (Żyżlewicz 2010).

In the present study, the content of reducing sugars and total sugars in potato tubers was not negatively affected by biostimulants. At harvest, glucose content was higher in skin than in flesh, ranging from 3.35 (cv. Satina in the control treatment) and 1.95 (cv. Irga in the Bio-Algeen S-90 treatment) to 7.44 and 6.20 g · kg^{-1} DM (cv. Valfi in the Kelpak treatment). Glucose concentration in whole tubers (6.65 g · kg^{-1} DM) was highest in cv. Valfi treated with Kelpak. Glucose content in the skin of potato tubers increased in cv. Satina and decreased (not significantly) in cv. HB Red treated with biostimulants; in the remaining cultivars, biostimulants exerted varied effects on glucose concentrations in skin. Glucose concentration increased

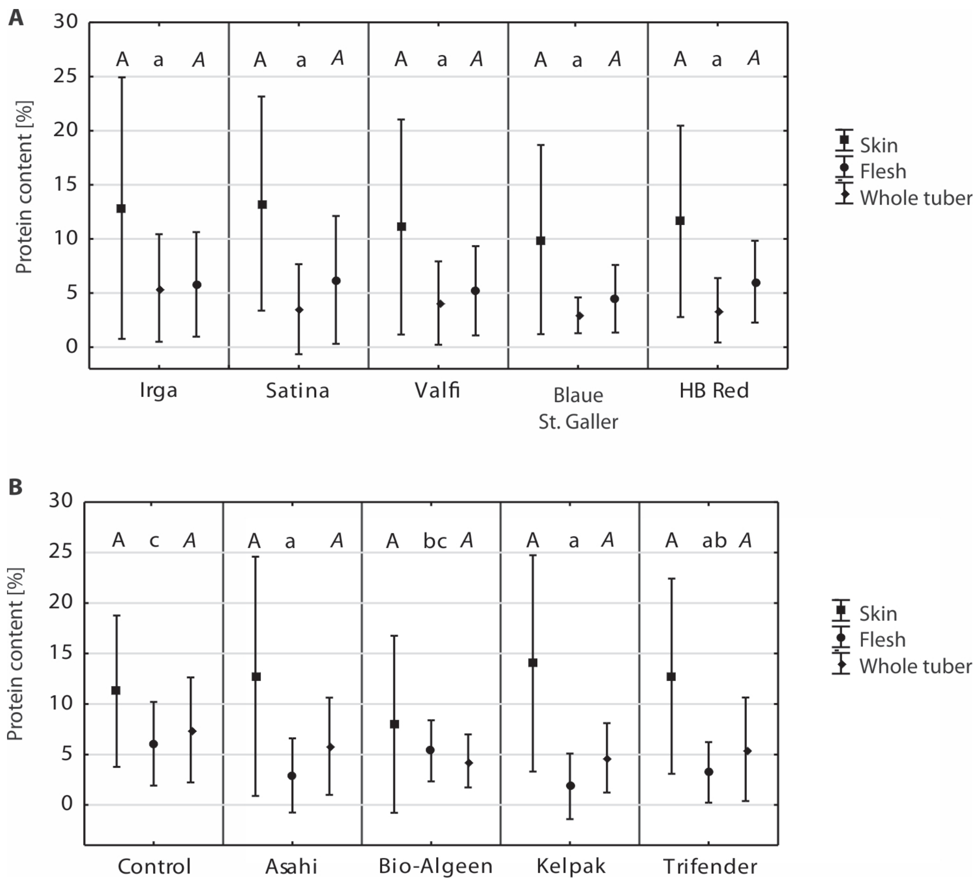

Fig. 2. Changes in the total protein content of potato tubers after storage in dependent cultivar (A) and biostimulant (B). Values followed by the same letters do not differ significantly in Tukey's (HSD) test ($p < 0.05$). Capital letters – skin, small letters – flesh, italic letters – whole tubers

in the flesh and whole tubers of the analyzed potato cultivars, with the exception of cv. Irga treated with Asahi SL and Bio-Algeen S-90 and cv. Valfi treated with Asahi SL (whole tubers) (Table 2). Fructose content was lower than glucose content by the following (maximum) values: skin 50–52% (cv. Irga in the Bio-Algeen S-90 treatment, cv. Blaue St. Galler in the control treatment), flesh – 56–59% (cv. Irga in control and Bio-Algeen S-90 treatments), whole tubers – 48–54% (cv. Irga in control and Bio-Algeen S-90 treatments, cv. Blaue St. Galler in the control treatment). Tubers (all tuber parts and whole tubers) of cv. Valfi treated with Kelpak SL had the highest fructose content (approx. 6 g · kg^{-1} DM, Table 2).

The content of total reducing sugars was higher in the skin than in the flesh of potatoes, which is consistent with the concentrations of individual simple sugars. The greatest amounts of reducing sugars, as well as glucose and fructose, in skin, flesh and whole tubers were noted in cv. Valfi treated with Kelpak SL (13.39, 11.89 and 12.44 g · kg^{-1} DM, respectively; Table 2). The content of total reducing sugars in tubers was higher in purple- and red-fleshed cultivars than in cream- and yellow-fleshed cultivars. The concentrations of total reducing sugars were significantly lower in the skin, flesh and whole tubers of cv. Irga, relative to the remaining cultivars (except for the skin of cv. Satina) (Fig. 3).

In comparison to the control treatment, the content of reducing sugars increased significantly in the flesh and whole tubers (except in the Asahi SL treatment), and in the skin of potato tubers in Bio-Algeen S-90 and Kelpak SL treatments (Fig. 4). In the work of Maciejewski *et al.* (2007), foliar application of Asahi SL and Atonik SL biostimulants caused a minor decrease in the accumulation of reducing sugars in tubers of cv. Ditta, and an increase in tubers of cv. Satina. Trawczyński (2014) reported that an amino-acid based biostimulant had no significant influence on the content of reducing sugars in tubers of cv. Satina. Baranowska and Mystkowska (2019) demonstrated that the genetic traits of potato cultivars (Owacja, Bellarosa and Vineta) and the applied biostimulants (GreenOk – Universal Pro and Asahi SL, alone and in combination with herbicides) had no significant effect on the content of total sugars or reducing sugars in tubers. In the experiment conducted by Ezzat *et al.* (2011), foliar application of seaweed extract and 50% of the recommended NPK fertilizer rate significantly accelerated plant growth, increased tuber yields and improved tuber quality by decreasing the content of reducing sugars and increasing

Table 2. Effects of cultivar and biostimulant on the reducing sugar content of potato tubers

Cultivar	Biostimulant	Glucose			Fructose			Total reducing sugars		
		skin	flesh	whole tuber	skin	flesh	whole tuber	skin	flesh	whole tuber
Irga	Control	4.39 a-d	2.35 abc	3.09 ab	2.76 abc	1.04 ab	1.66 ab	7.15 a-d	3.39 ab	4.76 ab
	Asahi	3.86 ab	2.29 abc	2.87 a	2.82 abc	1.15 ab	1.77 ab	6.68 a	3.44 ab	4.64 ab
	Bio-Algeen	4.61 a-d	1.95 a	2.89 a	2.28 a	0.81 a	1.33 a	6.88 ab	2.76 a	4.22 a
	Kelpak	4.36 a-d	2.57 a-d	3.34 ab	2.84 a-d	1.77 a-d	2.23 abc	7.21 a-d	4.34 abc	5.57 abc
	Trifender	3.88 ab	3.72 c-f	3.78 a-d	2.81 abc	2.12 b-f	2.40 a-d	6.69 a	5.84 b-f	6.18 a-e
Satina	Control	3.35 a	2.05 a	2.78 a	3.04 a-f	1.61 abc	2.35 a-d	6.38 a	3.66 ab	5.13 a-b
	Asahi	4.31 abc	2.99 a-e	3.50 abc	3.22 a-g	2.00 a-e	2.46 a-e	7.53 a-e	4.99 a-e	5.96 a-d
	Bio-Algeen	6.25 c-f	5.84 ij	5.95 hi	4.45 e-i	4.16 hi	4.26 h	10.70 e-i	10.00 hi	10.21 ij
	Kelpak	4.41 a-d	2.95 a-e	3.49 abc	2.82 abc	2.30 b-f	2.48 a-e	7.22 a-d	5.25 a-f	5.96 a-d
	Trifender	4.44 a-d	3.67 c-f	3.97 a-e	2.76 abc	2.03 a-e	2.30 abc	7.20 a-d	5.70 b-f	6.27 a-f
Valfi	Control	5.50 a-f	2.64 a-d	3.91 a-e	4.25 c-h	2.20 b-f	3.11 c-h	9.75 a-h	4.84 a-d	7.03 b-g
	Asahi	4.07 abc	3.67 c-f	3.83 a-e	2.89 a-e	2.65 c-g	2.78 b-g	6.96 a-c	6.32 c-f	6.61 a-f
	Bio-Algeen	5.86 b-f	4.23 e-h	4.84 c-h	4.57 f-i	2.98 g-h	3.57 e-h	10.43 d-i	7.21 d-g	8.41 d-i
	Kelpak	7.44 f	6.18 j	6.65 i	5.95 i	5.71 j	5.80 i	13.39 i	11.89 i	12.44 j
	Trifender	4.82 a-e	4.03 d-g	4.39 b-g	4.04 c-h	3.38 f-i	3.67 fgh	8.87 a-h	7.41 efg	8.06 d-i
Blaue St. Galler	Control	5.13 a-e	2.15 ab	3.43 abc	2.45 ab	1.27 ab	1.80 ab	7.59 a-e	3.42 ab	5.23 ab
	Asahi	4.58 a-d	3.98 d-g	4.26 a-g	3.73 a-h	3.27 e-i	3.47 d-h	8.31 a-g	7.25 d-g	7.73 c-h
	Bio-Algeen	5.88 b-f	4.64 f-i	5.12 d-h	4.44 e-i	3.03 d-h	3.57 e-h	10.32 c-i	7.67 fgh	8.69 f-i
	Kelpak	5.23 a-e	5.63 hij	5.47 f-i	3.92 b-h	3.90 ghi	3.90 gh	9.15 a-h	9.53 ghi	9.38 hi
	Trifender	5.05 a-e	5.34 g-j	5.22 d-i	2.92 a-e	3.67 ghi	3.36 c-h	7.97 a-f	9.01 gh	8.58 e-i
HB Red	Control	6.99 ef	2.31 abc	3.98 a-f	4.69 ghi	1.30 ab	2.53 b-f	11.67 g-i	3.61 ab	6.51 a-f
	Asahi	5.77 b-f	5.29 g-j	5.49 ghi	4.39 d-i	3.99 hi	4.17 h	10.16 b-i	9.28 gh	9.66 hi
	Bio-Algeen	6.84 ef	4.25 e-h	5.28 e-i	5.01 hi	3.22 e-i	3.91 gh	11.85 hi	7.47 e-h	9.19 ghi
	Kelpak	5.76 b-f	4.83 f-j	5.25 d-i	3.31 a-g	4.35 i	3.90 gh	9.07 a-h	9.18 gh	9.15 ghi
	Trifender	6.52 def	5.42 g-j	5.89 hi	4.66 ghi	3.62 ghi	4.06 h	11.18 f-i	9.03 gh	9.94 hi

Values followed by the same letters in columns do not differ significantly at $p \leq 0.05$

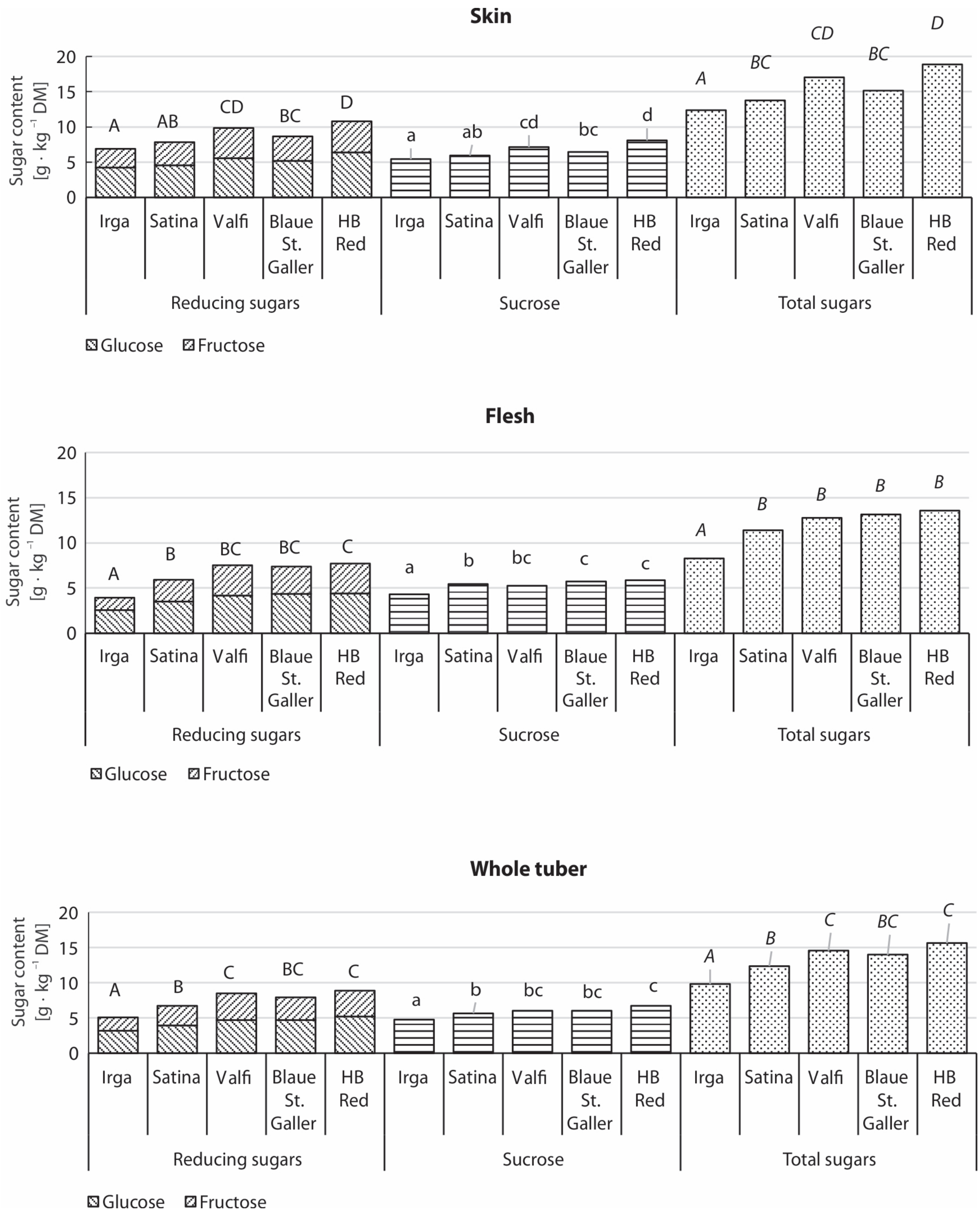

Fig. 3. Effect of cultivar on the sugar content of potato tubers at harvest (means of two-year study).
Values followed by the same letters do not differ significantly in Tukey's (HSD) test ($p < 0.05$). Capital letters – reductig sugars, small letters – sucrose, italic letters – total sugars

starch content. Arafa *et al.* (2012) found that foliar application of seaweed extract (*A. nodosum*), applied alone and in combination with potassium fertilizer (40 kg · ha^{-1} K_2O), increased the soluble sugar content of potato cultivars (from 42.25 to approx. 80 mg · g^{-1} FM), compared to the control treatment. Zarzecka and Gugała (2018) reported a significant increase in the content of total sugars and reducing sugars in potato cultivars in response to the application of Asahi SL growth regulator and the herbicide metribuzin. Kalinowski *et al.* (2018) demonstrated that the content of simple sugars in tubers of very early potato cultivars was not affected by genotype. The above authors also found that the Tytanit® growth stimulator (8.5 g Ti per dm^3) did not modify the content of simple sugars in tubers harvested 75 days after planting, i.e., at the end of June. Wadas and Dziugiel (2020) also observed that the content of total sugars, simple sugars and sucrose in young potato tubers did not change in response to biostimulants. However, Bio-Algeen S-90 increased

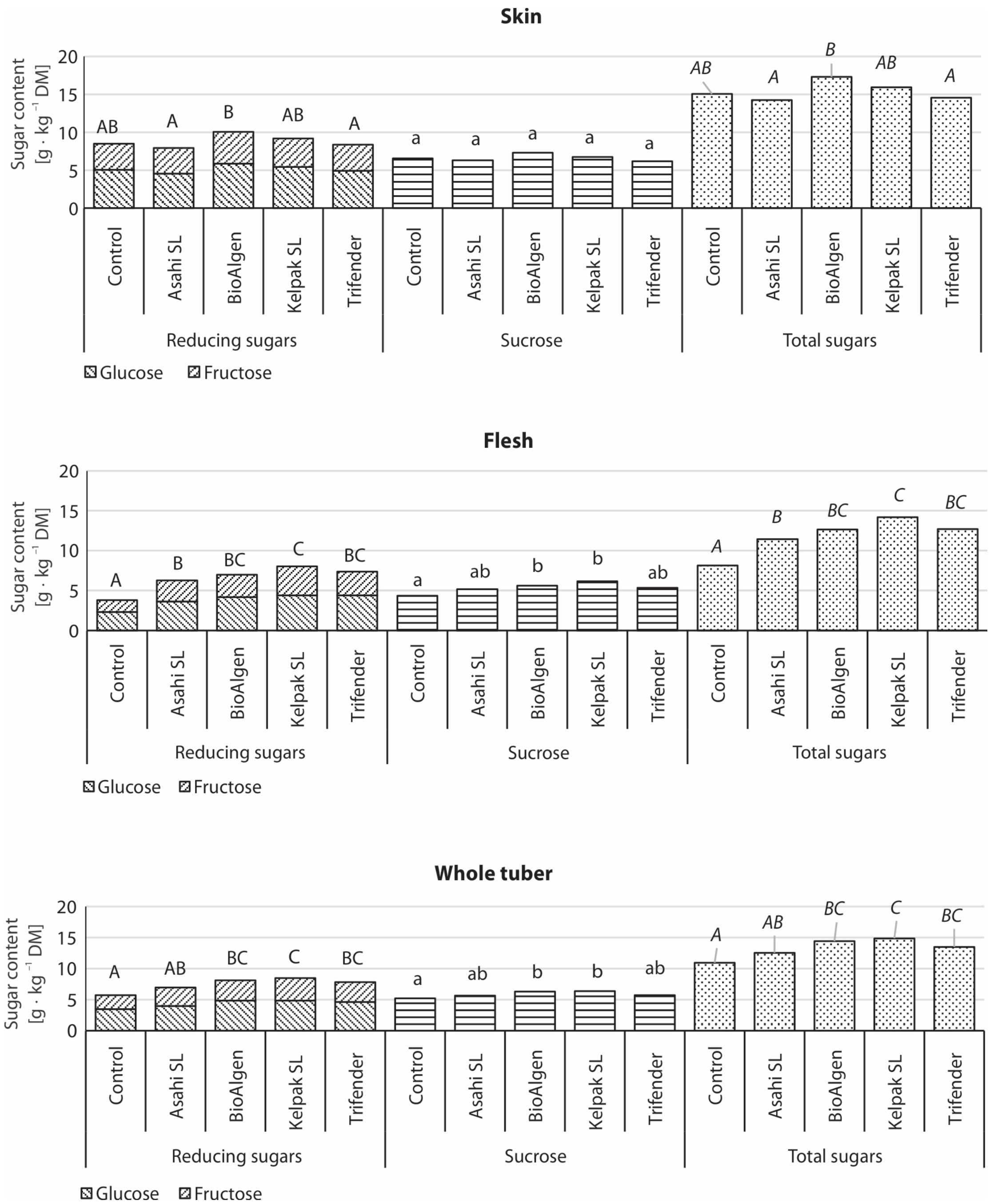

Fig. 4. Effect of biostimulant on the sugar content of potato tubers at harvest (means of two-year study).
Values followed by the same letters do not differ significantly in Tukey's (HSD) test ($p < 0.05$). Capital letters – reductig sugars, small letters – sucrose, italic letters – total sugars

the starch content of tubers in all analyzed potato cultivars (by 4.8 g · kg^{-1} on average), relative to the control treatment without biostimulants.

In the current study, the accumulation of reducing sugars in tubers of all analyzed potato cultivars increased during storage, particularly in cv. Satina where the content of monosaccharides increased by 27.5% in skin, by 68.8% in flesh and by 47.8% in whole tubers with skin. The content of total reducing sugars decreased in tubers of potato plants treated with biostimulants. The content of simple sugars was significantly lower in the flesh and whole tubers with skin (excluding the Asahi SL treatment) of the analyzed potato cultivars (Fig. 5). Potatoes should be stored at 3–5°C due to reduced rates of respiration, transpiration and sprouting, but the content of sucrose and reducing sugars in tubers increases under such storage conditions (Sowa-Niedziałkowska and Zgórska 2005). The quality of potato tubers is considerably affected not only by cultivar, but also by storage temperature and time. Matsuura-Endo *et al.* (2006), who stored tubers of five potato cultivars at various temperatures (2, 6, 8,

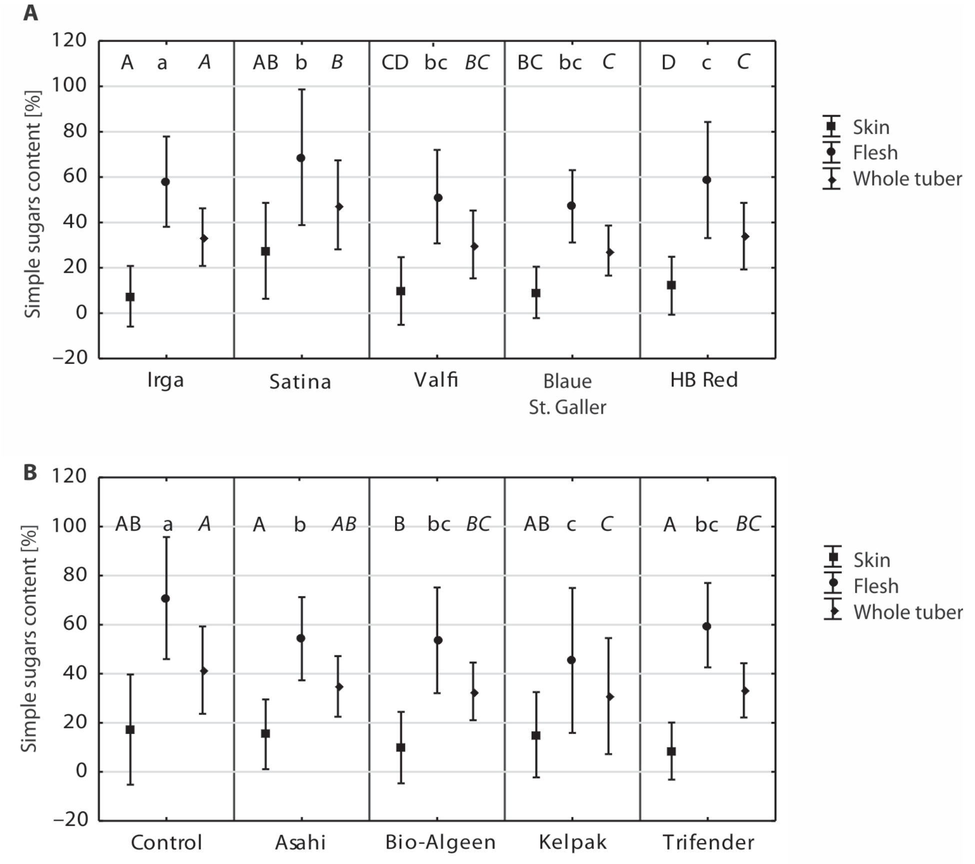

Fig. 5. Changes in the content of total simple sugars in potato tubers after storage in dependent cultivar (A) and biostimulant (B). Values followed by the same letters do not differ significantly in Tukey's (HSD) test ($p < 0.05$). Capital letters – skin, small letters – flesh, italic letters – whole tubers

10 and 18°C) for 18 weeks, found that the content of reducing sugars in tubers increased markedly at temperatures lower than 8°C, whereas only minor changes were noted in the content of free amino acids. The cited authors also observed that when the fructose/asparagine ratio was >2 during storage at low temperatures, asparagine content rather than reducing sugar content was the limiting factor for acrylamide formation. In a study by Grudzińska (2012), reducing sugars tended to accumulate in larger quantities in potato tubers stored at 2–4°C than in those stored at 8–10°C.

At harvest, the sucrose content of skin in cream- and yellow-fleshed tubers did not exceed 6 g · kg^{-1} DM (except for cv. Satina in the Bio-Algeen S-90 treatment). The content of this disaccharide was higher in purple- and red-fleshed cultivars (maximum values): cv. Valfi – 8.69 (Kelpak SL), cv. Blaue St. Galler – 7.74 (Bio-Algeen S-90), cv. HB Red – 9.14 g · kg^{-1} DM (control) (Table 3). In comparison to cream- and yellow-fleshed cultivars, sucrose concentration was significantly higher in the skin of cvs. Valfi and HB Red, in the flesh of cvs. Blaue St. Galler and HB Red, and in whole tubers of cv. HB Red (Fig. 3). Biostimulants had no significant effect on the sucrose content of skin in the analyzed potato cultivars. The sucrose content of flesh and whole tubers was higher in potato plants treated with biostimulants, and significant differences were found between Bio-Algeen S-90 and Kelpak SL treatments vs. the control treatment (Fig. 4). Biostimulants containing microorganisms convert nutrients from unavailable to plant-available forms. Fungi of the genus *Trichoderma* (including *T. asperellum* in Trifender WP) compete with phytopathogens for nutrients. Zarzecka *et al.* (2019) reported that the content of reducing sugars in potato tubers increased significantly, whereas the content of sucrose and total sugars did not change under the influence of soil conditioner UGmax. In the present study, the sucrose content of potato tubers increased during storage, by 12.4% in skin (cv. Satina), by 30% (cvs. Irga and Blaue St. Galler) to approximately 40% (cvs. Satina and Valfi) in flesh, and by 6.6% (cv. Irga) to 20% (cv. Satina) in whole tubers. In most cases, the effect of biostimulants on the sucrose content of skin, flesh and whole tubers during storage was not significant, and the maximum increase reached around 10% (in control and Kelpak SL treatments), 45% (Asahi SL) and 20% (Trifender WP), respectively (Fig. 6). In an experiment performed by Grudzińska *et al.* (2016), the sucrose content of freshly-harvested tubers ranged from 1.0 (cv. Gwiazda) to 2.2 g · kg^{-1} FM (cv. Stasia). Amjad *et al.* (2019) observed lower invertase activity and a lower

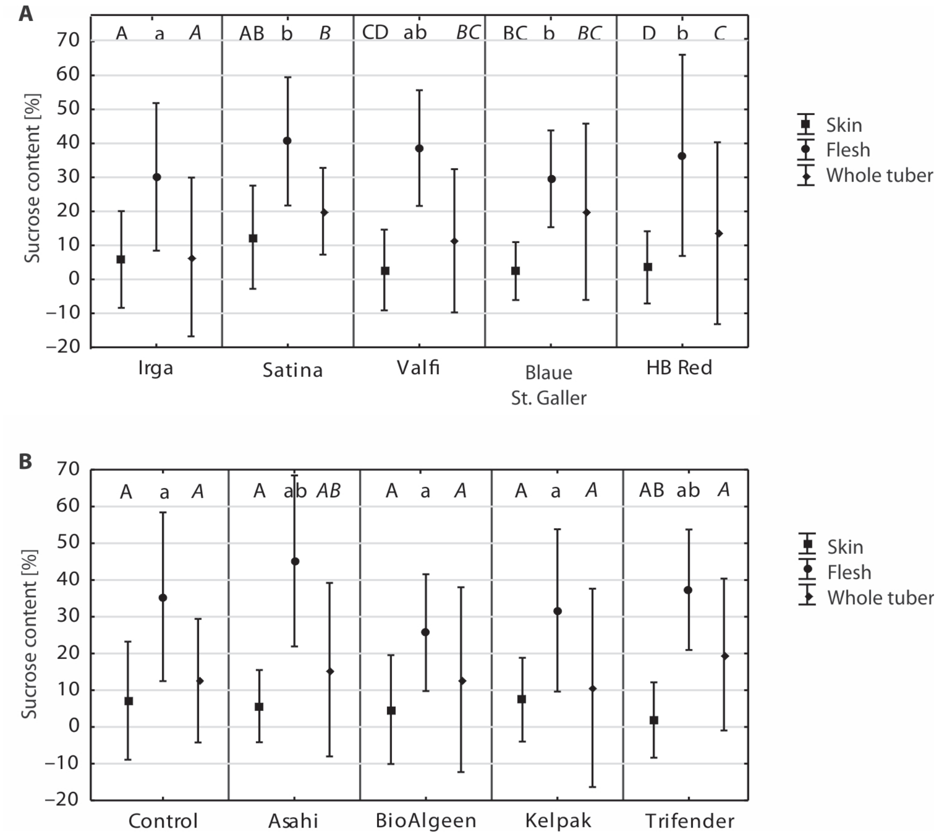

Fig. 6. Changes in the sucrose content of potato tubers after storage in dependent cultivar (A) and biostimulant (B).
Values followed by the same letters do not differ significantly in Tukey's (HSD) test ($p < 0.05$). Capital letters – skin, small letters – flesh, italic letters – whole tubers

content of reducing sugars in potato tubers stored at 7°C, than at 3°C (98–138 and 134–397 mg · g^{-1} FW in cvs. Lady Rosetta and Kuroda, respectively). Zhang and Lu (2021) found that invertase activity increased when potato tubers were stored at 2°C. Three to 6 days of storage were required to activate invertase. As a result, the content of reducing sugars in tubers increased significantly (approx. 2.5 to 3.8 times). Increased sucrose accumulation was also noted at 2°C.

At harvest, the total sugar content of skin in cream- and yellows-fleshed cultivars (Irga and Satina) ranged from 11.64 (control treatment) to 17.93 g · kg^{-1} DM (Bio-Algeen S-90) in cv. Satina. The total sugar content of skin was higher in purple- and red-fleshed cultivars, ranging from 13.17 (Asahi SL) to 22.08 g · kg^{-1} DM (Kelpak SL) in cv. Valfi. The total sugar content of flesh and whole tubers was the highest (approx. 20 g · kg^{-1} DM) in cv. Valfi treated with Kelpak SL (Table 3).

Table 3. Effects of cultivar and biostimulant on the sucrose and total sugar content of potato tubers

Cultivar	Biostimulant	Sucrose			Total sugars		
		skin	flesh	whole tuber	skin	flesh	whole tuber
Irga	Control	5.45 ab	4.89 a-f	5.09 abc	12.60 abc	8.28 ab	9.85 ab
	Asahi	5.76 abc	4.72 a-f	5.12 a-d	12.44 ab	8.16 ab	9.76 ab
	Bio-Algeen	5.68 abc	2.85 a	3.86 a	12.56 abc	5.61 a	8.08 a
	Kelpak	4.88 a	3.98 abc	4.37 ab	12.09 a	8.32 abc	9.94 ab
	Trifender	5.40 ab	5.17 b-f	5.26 a-e	12.09 a	11.00 b-h	11.45 a-e
Satina	Control	5.26 ab	5.22 b-f	5.22 a-e	11.64 a	8.89 a-d	10.36 abc
	Asahi	5.68 abc	4.68 a-e	5.06 abc	13.21 abc	9.67 a-f	11.02 a-d
	Bio-Algeen	7.23 a-e	7.58 h-i	7.66 gh	17.93 b-f	17.58 jk	17.87 hi
	Kelpak	5.81 abc	4.86 a-f	5.18 a-d	13.03 abc	10.10 b-g	11.14 a-d
	Trifender	5.73 abc	4.97 b-f	5.25 a-e	12.93 abc	10.67 b-h	11.52 a-e

Table 3. Effects of cultivar and biostimulant on the sucrose and total sugar content of potato tubers – *continuation*

Cultivar	Biostimulant	Sucrose			Total sugars		
		skin	flesh	whole tuber	skin	flesh	whole tuber
Valfi	Control	6.86 a-e	4.12 a-d	5.34 a-e	16.61 a-f	8.96 a-e	12.37 b-f
	Asahi	6.21 a-d	4.52 a-e	5.22 a-e	13.17 abc	10.84 b-h	11.82 a-e
	Bio-Algeen	7.58 b-e	5.22 b-f	6.10 b-h	18.00 b-f	12.43 d-i	14.50 d-h
	Kelpak	8.69 de	7.39 ghi	7.84 h	22.08 f	19.28 k	20.28 i
	Trifender	6.44 a-d	4.98 b-f	5.64 a-f	15.30 a-e	12.39 c-i	13.70 b-g
Blaue St. Galler	Control	6.07 abc	3.66 ab	4.68 ab	13.65 a-d	7.07 ab	9.91 ab
	Asahi	6.07 abc	5.74 c-h	5.89 b-h	14.38 a-d	12.99 e-i	13.62 b-g
	Bio-Algeen	7.74 b-e	6.08 d-i	6.72 c-h	18.06 c-f	13.75 f-j	15.41 e-h
	Kelpak	6.72 a-e	7.81 i	7.38 fgh	15.86 a-e	17.34 jk	16.75 ghi
	Trifender	5.70 abc	5.44 b-g	5.55 a-f	13.67 a-d	14.45 hij	14.13 c-h
HB Red	Control	9.14 e	3.90 abc	5.79 a-g	20.81 ef	7.52 ab	12.29 b-f
	Asahi	7.75 b-e	6.30 e-i	6.88 c-h	17.91 b-f	15.58 ijk	16.54 ghi
	Bio-Algeen	8.16 cde	6.36 e-i	7.05 d-h	20.00 ef	13.83 g-j	16.24 fgh
	Kelpak	7.66 b-e	6.73 f-i	7.14 e-h	16.72 a-f	15.91ijk	16.29 f-i
	Trifender	7.75 b-e	6.13 d-i	6.82 c-h	18.93 def	15.16 ijk	16.76 ghi

Values followed by the same letters in columns do not differ significantly at $p \leq 0.05$

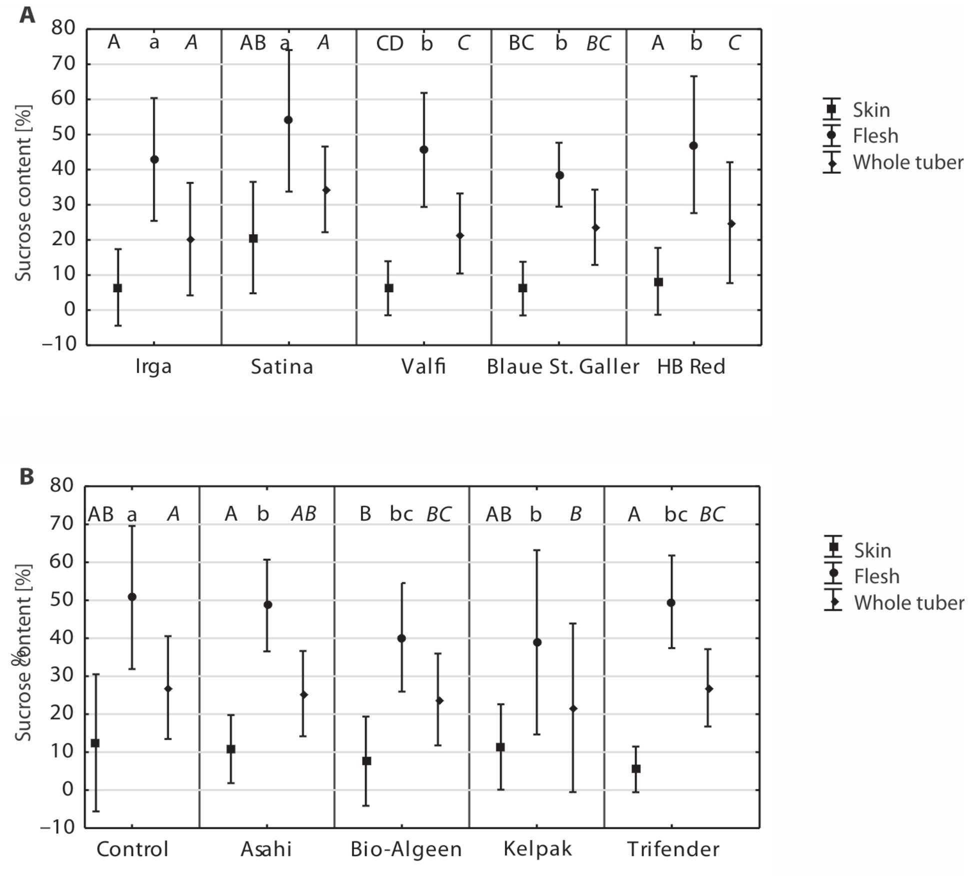

Fig. 7. Changes in the content of total sugars in potato tubers after storage in dependent cultivar (A) and biostimulant (B).
Values followed by the same letters do not differ significantly in Tukey's (HSD) test ($p < 0.05$). Capital letters – skin, small letters – flesh, italic letters – whole tubers

At harvest, the analyzed cultivars differed in the total sugar content of tubers (skin, flesh, whole tubers with skin). Total sugar content was lowest in cv. Irga (significant differences relative to the remaining cultivars), and highest in cv. HB Red (Fig. 3). The flesh and skin of tubers treated with biostimulants had significantly higher total sugar content (except for whole tubers in the Asahi SL treatment) than control tubers. The skin of tubers treated with Bio-Algeen S-90 had the highest total sugar content (Fig. 4). In the work of Saar-Reismaa *et al.* (2020), tubers of cv. Blue Congo and its cross-breed Granola (Blue Congo – violet skinned with violet flesh, Granola – yellow skinned with blanched yellow flesh) had the highest content of total sugars (glucose, fructose, sucrose and myo-inositol) – 34.1 mg · g^{-1} DW on average. High total sugar content was linked with high concentrations of copper and calcium, and anthocyanin concentration was correlated with total sugar content. In an earlier study by Piikki *et al.* (2003), the content of sucrose, glucose and fructose in potato tubers reached 6.4–21.8, 2.3–29.7 and 1.2–25.4 mg · g^{-1} DW, respectively. Duarte-Delgado *et al.* (2016) reported that total sugar concentration in potato tubers ranged from 7.5 to 74.1 mg · g^{-1} DW.

After storage, an increase in the total sugar content of the analyzed tuber parts was significantly higher in cv. Satina (20.7%, 53.9% and approx. 34.4%, respectively) than in the remaining cultivars. In biostimulant treatments, total sugar content did not increase significantly in skin, and it decreased by 11.8% and 5.3% in flesh and whole tubers, respectively, in the Kelpak SL treatment, relative to the control treatment (Fig. 7). Żołnowski (2010) demonstrated that the content of reducing sugars and total sugars increased by 6% and 30%, respectively, in potato tubers stored at 6°C. In a study by Bhattacharjee *et al.* (2014), the content of reducing sugars and total sugars increased in potato tubers stored for 100 days, in all analyzed cultivars. In the current study, at harvest and after storage, the highest total sugar content of potato tubers was 6.1 g and 8.2 g · kg^{-1} FM, respectively, whereas the lowest was – 4.4 and 6.3 g · kg^{-1} FM, respectively.

Conclusions

The quality parameters of potato tubers, i.e., the content of protein and reducing sugars (glucose and fructose), sucrose and total sugars, were affected by the genotype rather than by the applied biostimulants. The amounts of these compounds were higher in the skin, flesh and whole tubers with skin of purple- and red-fleshed cultivars, than in cream- and yellow-fleshed cultivars. The content of reducing sugars in tubers remained within the normal reference range. No significant differences in the total protein content of tubers were found between the experimental treatments with biostimulant application and the control treatment without biostimulant application. Tubers (skin, flesh, whole tubers with skin) of potato plants treated with biostimulants (in particular Bio-Algeen S-90 and Kelpak SL) accumulated more reducing sugars and sucrose. The concentrations of protein, reducing sugars, sucrose and total sugars in tubers increased during storage. Edible potato cultivars with colored flesh, treated with biostimulants, provide tubers rich in nutrients, which are available all year round. Biostimulants should be carefully selected so as to meet the specific needs of each cultivar.

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