

Article

Effect of Plant Biostimulants on Macronutrient Content in Early Crop Potato Tubers

Tomasz Dziugiel¹ and Wanda Wadas^{2,*} 

¹ Main Inspectorate of Plant Health and Seed Inspection, Voivodeship Plant Health and Seed Inspection Service, Żólkiewskiego 17, 05-075 Warszawa-Wesoła, Poland; tomasz_dziugiel@wp.pl

² Institute of Agriculture and Horticulture, Faculty of Agrobioengineering and Animal Husbandry, Siedlce University of Natural Sciences and Humanities, B. Prusa 14, 08-110 Siedlce, Poland

* Correspondence: wanda.wadas@uph.edu.pl

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Abstract: This paper analyzes the effects of the foliar application of the seaweed extracts Bio-algeen S90 (*Ascophyllum nodosum*) and Kelpak SL (*Ecklonia maxima*), as well as the humic and fulvic acids in HumiPlant (leonardite extract) on the macronutrient content in tubers of very early potato cultivars ('Denar', 'Lord', 'Miłek') and their ionic ratios. The field experiment was carried out in central-eastern Poland over three growing seasons, using Haplic Luvisol. The biostimulants were applied according to the manufacturers' recommendations. Potatoes were harvested 75 days after planting. The use of biostimulants increased potassium (K) content in tubers, on average, by 1.26 g·kg⁻¹ of dry matter compared with the untreated control tubers. Bio-algeen S90 did not affect the phosphorus (P) content in tubers, whereas Kelpak SL and HumiPlant reduced the phosphorus content, on average, by 0.063 g·kg⁻¹ of dry matter. The biostimulants did not affect calcium (Ca), magnesium (Mg), or sodium (Na) content in tubers. The use of biostimulants resulted in an increase in the mass ratios of K⁺:Ca²⁺, K⁺:Mg²⁺, and (K⁺ + Na⁺):Ca²⁺ + Mg²⁺ in early crop potato tubers, compared with the untreated control tubers, but did not affect the mass ratios of Na⁺:Ca²⁺ and Na⁺:Mg²⁺ or the mass ratio of Ca:P. The macronutrient content in early crop potato tubers and their ionic ratios depended on the cultivar and environment conditions.

Keywords: seaweed extract; humic acids; new potatoes; mineral elements; ionic ratios

1. Introduction

Potato (*Solanum tuberosum* L.) tubers contain 1.0–1.2% of mineral compounds. Potassium (K) is the basic mineral in potato (150–1386 mg·100 g⁻¹ of fresh weight FW). Phosphorus (P) and magnesium (Mg) are present in potato tubers in moderate quantities (42–120 mg·100 g⁻¹ FW and 16–40 mg·100 g⁻¹ FW, respectively), while calcium (Ca) is present in small quantities (2–20 mg·100 g⁻¹ FW). The bioavailability of mineral elements from potatoes is potentially high due to high concentrations in potato tubers of organic compounds that stimulate the absorption of minerals by humans. Potatoes are a source of substantial quantities of minerals in the human diet, due to their large consumption (150–800 g per day). Two hundred grams of boiled potatoes (a typical meal) provides up to 30% of the recommended daily intake of K, 15% of Mg, and 12% of P [1,2]. The chemical composition of potato tubers is affected by different pre-harvest and post-harvest factors [1,3].

The use of biostimulants can enhance soil nutrient availability, plant nutrient uptake, and assimilation and increase mineral content in plant-based food. The major plant biostimulants that affect root growth and nutrient uptake are seaweed extracts and humic substances. Seaweed extracts and humic substances improve plant nutrition by affecting soil properties (improvement of the soil structure or improvement of micronutrient solubility in the soil) and by directly affecting the plant's

physiology (changes in root morphology, an increase in root activity of H⁺ ATPase, an increase in the activity of NO₃-assimilation enzymes, or an increase in root colonisation by arbuscular mycorrhizal fungi) [4,5].

Seaweed extracts contain plant hormones such as auxins, cytokinins, and abscisic acid, and polysaccharides that affect plant nutrition. Seaweed extracts enhance plant nutrient uptake by their effect on the expression of some genes encoding root nutrient transports. Most commercial seaweed extracts are manufactured from brown seaweeds such as *Ascophyllum nodosum* (*A. nodosum*), *Ecklonia maxima* (*E. maxima*), *Laminaria* spp., or *Sargassum* spp. [4,6,7]. Commercial *A. nodosum* extract Bio-algeen S90 increased K, P, and Ca content in cherry tomato but did not affect Mg content [8]. Bio-algeen S90 increased Mg and sodium (Na) content in carrot roots and, at the same time, slightly decreased the content of K and P, and distinctly reduced the content of Ca [9]. Commercial *E. maxima* extract Kelpak SL increased Mg, Ca, Na, K, and P content in carrot roots [10]. Bio-algeen S90 and Kelpak SL decreased K and Ca content in potato tubers, but did not affect the content of Mg, P, or Na [11]. The concentration of most minerals is higher in the skin than in the flesh of potato tubers [12]. Bio-algeen S90 increased P content in the skin and Mg content in the flesh, whereas Kelpak SL increased Ca content both in the flesh and in the skin and K content in the skin [13]. Other products based on *A. nodosum* extract Primo increased P and K content in potato tubers [14], and *E. maxima* extract Afrikelp LG-1 increased K, P, Ca, Mg, and Na content in potato leaves [15].

Biostimulants based on humic substances (humic acids, fulvic acids, humins) exert both structural and physiological changes in roots and shoots related to nutrient uptake, assimilation, and distribution. The positive effect of humic substances on plant metabolism is related to the phytohormone-like activity (auxins, cytokinins, or gibberellins) of some of their components and on indoleacetic acid (IAA)-independent mechanisms. The biological activity of humic substances depends on their origin, chemical structure, and concentrations. Leonardite is a commercial humic substance most commonly used in manufacturing [16–18]. Foliar application of humic acids increased the K, P, Ca, and Mg content in leaves of cucumber plants [19] and K, P, and Ca in tomato plants [20]. Soil or foliar application of humic and fulvic acids increased the K and P content in potato tubers [21]. According to some authors, humic acid is generally ineffective for improving vegetable crop nutrient uptake or productivity [22].

The current study aimed to determine the effect of foliar application of seaweed extracts and humic and fulvic acids on the macronutrient contents in early crop potato tubers and their ionic ratios. In the study, it was hypothesised that seaweed extracts and humic acids could contribute to enhancing mineral contents in potato tubers. The assumption was also made that potato response to the application of these biostimulants depends on the cultivar and the environmental conditions.

2. Materials and Methods

2.1. Plant Material and Growth Conditions

The study material included tubers of very early potato cultivars treated with plant biostimulants, obtained from a field experiment carried out in central-eastern Poland (52°03' N; 22°33' E) over three growing seasons (2012–2014).

The field experiment was carried out on Haplic Luvisol (LV-ha) with a sandy loam texture, according to the World Reference Base for soil resources WRB [23]. The soil was characterised by an acidic-to-slightly-acid reaction, a high content of available P, a medium-to-high content of K, and a low-to-medium content of Mg (Table 1).

The weather conditions during the potato growth period were different (Table 2). The year 2012 was warm and moderately wet. The next year, 2013 was warm and with heavy rainfall, whereas 2014 was cool with heavy rainfall after the plant emergence and drought in the period of tuber growth.

Table 1. Soil chemical properties at the experimental site.

Soil Chemical Properties	Years		
	2012	2013	2014
Organic carbon C _{org} (g·kg ⁻¹)	7.89	14.21	11.83
Soil pH _{KCl}	4.7	6.3	5.3
Available nutrients (mg·kg ⁻¹)			
P	122	144	118
K	208	124	191
Mg	22	40	51

Table 2. Weather conditions during the potato growth period.

Years	Months		
	April	May	June
Temperature (°C)			
2012	8.9	14.6	16.3
2013	7.4	15.3	18.0
2014	9.8	13.5	15.4
Many year (1996–2010)	8.0	13.5	17.0
Rainfall (mm)			
2012	29.9	53.4	76.2
2013	36.0	105.9	98.8
2014	45.0	92.7	55.4
Many year (1996–2010)	33.6	58.3	59.6
Hydrothermal Index			
2012	1.1	1.2	1.5
2013	1.6	2.2	1.8
2014	1.5	2.2	1.2

Hydrothermal index value: up to 0.4 extremely dry; 0.41–0.7 very dry; 0.71–1.0 dry; 1.01–1.3 quite dry; 1.31–1.6 optimal; 1.61–2.0 quite wet; 2.01–2.5 wet; 2.51–3.0 very wet; >3 extremely wet [24].

In each year of the study, spring triticale was grown as a potato forecrop. Farmyard manure was applied in autumn, at a rate of 25 t·ha⁻¹, and mineral fertilizers were applied at rates of 80 kg N (ammonium nitrate), 35 kg P (superphosphate), and 100 kg K (potassium sulphate) per hectare in spring. Potato cultivation was carried out according to common agronomical practice. Colorado potato beetle (*Leptinotarsa decemlineata*) was controlled using thiametoksam (Actara 25 WG; Syngenta Crop Protection AG, Basel, Switzerland) and chlotianidine (Apacz 50 WG; Sumitomo Chemical Co. Ltd., Tokyo, Japan).

2.2. Experimental Design

The field experiment was established in a split-plot design with three replications. The experimental factors were: factor A—plant biostimulant: control without biostimulant, Bio-algeen S90 manufactured by the Schulze & Hermsen GmbH, Dahlenburg, Germany (*A. nodosum* extract; according to the manufacturer containing amino acids, vitamins, alginic acids and other active components of seaweeds, macronutrients N, P, K, Ca, Mg and micronutrients B, Fe, Cu, Mn, Zn, Se, Co), Kelpak SL manufactured by the Kelp Products (Pty) Ltd., Simon's Town, South Africa (*E. maxima* extract containing auxin 11 mg·dm⁻³ and cytokinin 0.031 mg·dm⁻³), HumiPlant manufactured by the Varichem Ltd., Warsaw, Poland (leonardite extract containing humic acid 12% and fulvic acid 6%, macronutrients K, Ca, Mg, S and micronutrients Fe, Mn, B, Mo, Zn, Cu), and factor B—potato cultivar: 'Denar' (cooking type AB—multi-purpose potatoes to salad potatoes; tubers with a light yellow flesh), 'Lord' (cooking type

AB—multi-purpose potatoes to salad potatoes; tubers with a light yellow flesh), and ‘Mifek’ (cooking type BC—multi-purpose potatoes to floury potatoes; tubers with a light yellow flesh) [25].

The biostimulants, used in crop production based on the permission of the Ministry of Agriculture and Rural Development in Poland, were applied twice according to the manufacturers’ recommendations: Bio-algeen S90 at the beginning of leaf development stage (under the terms of uniform codes of phenologically similar growth stages of plant species of Biologische Bundesanstalt, Bundessortenamt and Chemical Industry the BBCH 10–11 stage) and two weeks after the first treatment, Kelpak SL at the leaf development stage (BBCH 14–16) and two weeks after the first treatment, HumiPlant at the leaf of development stage (BBCH 14–16) and one week after the first treatment [26]. In each treatment, the biostimulants were applied at the dose of 2 dm³·ha⁻¹. Potato plants sprayed with water were used as a control without a biostimulant.

Six-week pre-sprouted seed potatoes were planted on 12 April 2012, 18 April 2013, and 7 April 2014, with a row spacing of 0.250 m and 0.675 m between rows. The plots were six rows wide and 4 m long (96 plants per plot). Potatoes were harvested 75 days after planting on 26 June 2012, 3 July 2013, and 23 June 2014.

2.3. Laboratory Analysis

Laboratory studies were conducted on samples of 50 different-sized tubers taken from each plot. Potato tubers were analyzed for the content of P with the vanadium-molybdenum colorimetric method, K, Ca, and Na with the flame photometric method, and Mg with atomic absorption spectrometry (AAS) method following previous mineralisation of potato tuber samples [27]. The contents of macronutrients were expressed as grams per kilogram of potato tuber dry matter (DM).

The ionic (mass) ratios of K⁺:Ca²⁺, K⁺:Mg²⁺, Na⁺:Ca²⁺, Na⁺:Mg²⁺, (K⁺ + Na⁺):Ca²⁺ + Mg²⁺, and Ca:P were calculated.

2.4. Statistical Analysis

The results of the three-year study were analyzed statistically using analysis of variance (ANOVA) for the split-plot design. The significance of differences between the compared averages was verified using Tukey’s test at the significance level $p \leq 0.05$. Statistical calculations were performed in Excel software using the authors’ own algorithm based on the split-plot mathematical model:

$$y_{ijl} = m + a_i + g_j + e_{ij}^{(1)} + b_l + ab_{il} + e_{ijl}^{(2)}$$

where: y_{ijl} —the value of the examined characteristic (macronutrient content); m —population average; a_i —the effect of the i -th level of factor A (plant biostimulant); g_j —the effect of the j -th repetition; $e_{ij}^{(1)}$ —error 1 due to interaction of factor A and repetitions; b_l —the effect of the l -th level of factor B (potato cultivar); ab_{il} —the effect of interaction of factor A and B; $e_{ijl}^{(2)}$ —random error [28].

3. Results

3.1. Macronutrient Content

The biostimulants used in the experiment had a significant effect on the K and P content in potato tubers but did not affect the content of Ca, Mg, or Na (Table 3). Following the application of plant biostimulants, the K content in tubers was higher, on average, by 1.26 g·kg⁻¹ DM, compared with the control treatment without biostimulant. The plant biostimulant had the greatest effect on the K accumulation by potato tubers in the year with the lowest air temperature and drought during the tuber growth period. In that year (2014), following the application of biostimulants, the K content in tubers was higher, on average, by 2.60 g·kg⁻¹ DM, compared with the control treatment without biostimulant. Bio-algeen S90 did not affect the P content in potato tubers. Following the application of Kelpak SL and HumiPlant, the P content in tubers was lower, on average, by 0.063 g·kg⁻¹ DM, compared with the

control treatment without biostimulant. The plant biostimulant and year interaction effect on the P content in tubers was not found. No effect of plant biostimulant and potato cultivar interaction on the K and P content in tubers was also not found.

Table 3. Macronutrient content in potato tubers in relation to plant biostimulant.

Plant Biostimulant	Years			Cultivar			Mean
	2012	2013	2014	Denar	Lord	Milek	
Potassium–K (g·kg ⁻¹ dry matter–DM)							
Without biostimulant	20.14 b	20.99 a	18.28 b	19.85 a	19.36 a	20.19 a	19.80 b
Bio-algeen S90	22.38 a	20.97 a	20.87 a	21.77 a	21.25 a	21.20 a	21.41 a
Kelpak SL	21.15 ab	20.21 a	21.32 a	20.91 a	21.26 a	20.51 a	20.89 a
HumiPlant	21.25 ab	20.96 a	20.45 a	20.70 a	21.17 a	20.79 a	20.89 a
Phosphorus–P (g·kg ⁻¹ DM)							
Without biostimulant	2.659 a	2.326 a	2.579 a	2.507 a	2.453 a	2.603 a	2.524 a
Bio-algeen S90	2.758 a	2.330 a	2.578 a	2.489 a	2.680 a	2.497 a	2.555 a
Kelpak SL	2.654 a	2.312 a	2.504 a	2.513 a	2.511 a	2.447 a	2.490 ab
HumiPlant	2.590 a	2.206 a	2.500 a	2.376 a	2.469 a	2.451 a	2.432 b
Calcium–Ca (g·kg ⁻¹ DM)							
Without biostimulant	0.388 a	0.510 a	0.456 a	0.447 a	0.440 a	0.467 a	0.451 a
Bio-algeen S90	0.403 a	0.533 a	0.478 a	0.471 a	0.488 a	0.456 a	0.471 a
Kelpak SL	0.384 a	0.491 a	0.443 a	0.411 a	0.450 a	0.458 a	0.440 a
HumiPlant	0.374 a	0.504 a	0.443 a	0.441 a	0.432 a	0.449 a	0.441 a
Magnesium–Mg (g·kg ⁻¹ DM)							
Without biostimulant	1.353 a	1.094 a	1.238 a	1.239 a	1.240 a	1.207 a	1.229 a
Bio-algeen S90	1.376 a	1.124 a	1.243 a	1.229 a	1.289 a	1.226 a	1.248 a
Kelpak SL	1.312 a	1.148 a	1.220 a	1.243 a	1.236 a	1.201 a	1.227 a
HumiPlant	1.290 a	1.110 a	1.218 a	1.209 a	1.266 a	1.143 a	1.206 a
Sodium–Na (g·kg ⁻¹ DM)							
Without biostimulant	0.367 a	0.333 a	0.369 a	0.340 a	0.366 a	0.363 a	0.356 a
Bio-algeen S90	0.373 a	0.338 a	0.380 a	0.359 a	0.367 a	0.366 a	0.364 a
Kelpak SL	0.356 a	0.348 a	0.384 a	0.364 a	0.338 a	0.386 a	0.363 a
HumiPlant	0.349 a	0.350 a	0.407 a	0.350 a	0.392 a	0.363 a	0.369 a

Means within columns followed by the same letters do not differ significantly at $p \leq 0.05$.

The macronutrient content in early crop potato tubers depended on the cultivar and environment conditions during the potato growth (Table 4). Regardless of the treatment (with or without biostimulant), the content of K, P, Ca, and Na in tubers of the potato cultivars tested were similar, whereas tubers of 'Milek' contained lower levels of Mg than 'Denar' and 'Lord'.

Table 4. Macronutrient content in potato tubers in relation to potato growing season and cultivar.

Year and Cultivar	K (g·kg ⁻¹ DM)	P (g·kg ⁻¹ DM)	Ca (g·kg ⁻¹ DM)	Mg (g·kg ⁻¹ DM)	Na (g·kg ⁻¹ DM)
Year					
2012	21.23 a	2.665 a	0.388 c	1.333 a	0.361 ab
2013	20.78 ab	2.293 c	0.510 a	1.119 c	0.342 b
2014	20.23 b	2.540 b	0.455 b	1.230 b	0.385 a
Cultivar					
Denar	20.81 a	2.471 a	0.443 a	1.230 a	0.353 a
Lord	20.76 a	2.528 a	0.453 a	1.258 a	0.366 a
Milek	20.67 a	2.499 a	0.457 a	1.194 b	0.369 a

Means within columns followed by the same letters do not differ significantly at $p \leq 0.05$.

The most K, P, and Mg and, at the same time, the least Ca were accumulated by potato tubers in the warm and moderately wet growing season of 2012, which was characterized by the lowest soil pH value. The highest concentrations of Na were accumulated by potato tubers in 2014, with the lowest air temperature and with drought periods during the tuber growth. The content of P and Mg in the potato tubers decreased along with an increase in the soil pH values, whereas the content of Ca displays a gradient in the opposite direction. The soil pH value had no clear effect on the K and Na contents in tubers.

3.2. Macronutrient Ionic Ratios

The biostimulants used in the experiment had a significant effect on the mass ratios of $K^+ : Ca^{2+}$, $K^+ : Mg^{2+}$, and $(K^+ + Na^+) : (Ca^{2+} + Mg^{2+})$ in potato tubers but had no effect on mass ratios of $Na^+ : Ca^{2+}$ or $Na^+ : Mg^{2+}$ (Table 5).

Table 5. Macronutrient ionic ratios in potato tubers in relation to plant biostimulant.

Plant Biostimulant	Years			Cultivar			Mean
	2012	2013	2014	Denar	Lord	Milek	
$K^+ : Ca^{2+}$							
Without biostimulant	52.27 b	41.17 a	40.80 c	45.27 a	45.10 a	43.87 a	44.75 b
Bio-algeen S90	55.90 ab	39.64 a	44.06 bc	47.64 a	44.76 a	47.22 a	46.54 ab
Kelpak SL	55.02 ab	41.35 a	48.66 a	51.97 a	48.85 a	45.21 a	48.68 a
HumiPlant	57.42 a	41.98 a	46.40 ab	48.47 a	50.39 a	46.94 a	48.60 a
$K^+ : Mg^{2+}$							
Without biostimulant	14.92 a	19.16 a	14.86 b	16.19 a	15.86 a	16.90 a	16.32 b
Bio-algeen S90	16.32 a	18.81 a	16.82 a	17.80 a	16.59 a	17.56 a	17.31 ab
Kelpak SL	16.15 a	17.62 a	17.52 a	16.87 a	17.24 a	17.18 a	17.10 ab
HumiPlant	16.58 a	18.90 a	16.84 a	17.22 a	16.86 a	18.24 a	17.44 a
$Na^+ : Ca^{2+}$							
Without biostimulant	0.951 a	0.656 a	0.818 a	0.787 a	0.847 ab	0.790 a	0.808 a
Bio-algeen S90	0.931 a	0.636 a	0.806 a	0.782 a	0.775 b	0.816 a	0.791 a
Kelpak SL	0.932 a	0.715 a	0.887 a	0.901 a	0.780 b	0.852 a	0.844 a
HumiPlant	0.941 a	0.698 a	0.927 a	0.819 a	0.929 a	0.819 a	0.855 a
$Na^+ : Mg^{2+}$							
Without biostimulant	0.270 a	0.305 a	0.300 a	0.275 a	0.297 a	0.303 a	0.292 a
Bio-algeen S90	0.271 a	0.300 a	0.307 a	0.294 a	0.286 a	0.299 a	0.293 a
Kelpak SL	0.273 a	0.304 a	0.316 a	0.294 a	0.279 a	0.323 a	0.297 a
HumiPlant	0.272 a	0.316 a	0.335 a	0.292 a	0.312 a	0.319 a	0.308 a
$(K^+ + Na^+) : (Ca^{2+} + Mg^{2+})$							
Without biostimulant	11.79 b	13.28 a	11.05 b	12.00 a	11.81 a	12.29 a	12.04 b
Bio-algeen S90	12.82 ab	12.94 a	12.35 a	13.03 a	12.19 a	12.89 a	12.70 a
Kelpak SL	12.68 ab	12.55 a	13.09 a	12.85 a	12.84 a	12.62 a	12.77 a
HumiPlant	13.03 a	13.21 a	12.58 a	12.77 a	12.73 a	13.32 a	12.94 a
Ca:P							
Without biostimulant	0.146 a	0.220 a	0.146 a	0.181 a	0.180 a	0.181 a	0.181 a
Bio-algeen S90	0.148 a	0.229 a	0.148 a	0.192 a	0.186 a	0.185 a	0.188 a
Kelpak SL	0.146 a	0.213 a	0.146 a	0.165 a	0.183 a	0.189 a	0.179 a
HumiPlant	0.146 a	0.231 a	0.146 a	0.187 a	0.181 a	0.187 a	0.185 a

Means within columns followed by the same letters do not differ significantly at $p \leq 0.05$.

Following plant biostimulant application, the mass ratios of $K^+ : Ca^{2+}$, $K^+ : Mg^{2+}$, and $(K^+ + Na^+) : (Ca^{2+} + Mg^{2+})$ in potato tubers were broader, compared with the untreated control tubers. The

greater differences were found in 2012 and 2014 with the higher K content in soil and, at the same time, the lower soil pH than in 2013. The plant biostimulant and potato cultivar interaction effect on the mass ratio of $K^+ : Ca^{2+}$, $K^+ : Mg^{2+}$, and $(K^+ + Na^+) : (Ca^{2+} + Mg^{2+})$ in tubers was not found. The plant biostimulant applied had a significant effect on the $Na^+ : Ca^{2+}$ ratio only in the tubers of 'Lord'. Following the application of Bio-algeen S90 and Kelpak SL, the mass ratio of $Na^+ : Ca^{2+}$ for 'Lord' tubers was narrower than with the application of HumiPlant. The plant biostimulant applied had no effect on the mass ratio of Ca:P in tubers of the potato cultivars tested.

Regardless of the treatment (with or without biostimulant), the calculated mass ratios of macronutrient in tubers of the potato cultivars tested were similar, except the mass ratio of $Na^+ : Mg^{2+}$ (Table 6). The $Na^+ : Mg^{2+}$ ratio in tubers of 'Miłek' was higher than in 'Denar' and 'Lord'. The mass ratios of macronutrient in potato tubers depended on environment conditions (Table 6). The $K^+ : Mg^{2+}$, $Na^+ : Mg^{2+}$, $(K^+ + Na^+) : (Ca^{2+} + Mg^{2+})$, and Ca:P ratios were highest in the warm and moist growing season of 2013 and, at the same time, with the highest soil pH. In that year, the $K^+ : Ca^{2+}$ and $Na^+ : Ca^{2+}$ ratios were the lowest.

Table 6. Macronutrient ionic ratios in potato tubers in relation to potato growing season and cultivar.

Year and Cultivar	$K^+ : Ca^{2+}$	$K^+ : Mg^{2+}$	$Na^+ : Ca^{2+}$	$Na^+ : Mg^{2+}$	$(K^+ + Na^+) : (Ca^{2+} + Mg^{2+})$	Ca:P
Year						
2012	55.40 a	15.99 b	0.939 a	0.272 b	12.58 ab	0.146 c
2013	41.04 c	18.62 a	0.676 c	0.306 a	12.99 a	0.223 a
2014	44.98 b	16.51 b	0.859 b	0.314 a	12.27 b	0.180 b
Cultivar						
Denar	48.34 a	17.02 a	0.822 a	0.289 b	12.66 a	0.181 a
Lord	47.27 a	16.64 a	0.833 a	0.292 b	12.39 a	0.182 a
Miłek	45.81 a	17.47 a	0.819 a	0.311 a	12.78 a	0.185 a

Means within columns followed by the same letters do not differ significantly at $p \leq 0.05$.

4. Discussion

The application of the seaweed extracts Bio-algeen S90 (*A. nodosum*) and Kelpak SL (*E. maxima*), as well as the humic and fulvic acids in HumiPlant (leonardite extract) increased marketable tuber yield 75 days after planting (the end of June) of very early potato cultivars 'Denar', 'Lord', and 'Miłek', on average, by $2.15 \text{ t} \cdot \text{ha}^{-1}$, but it did not affect the dry matter content in tubers, presented in earlier papers [29,30]. Increased tuber yield can be associated with a reduction in the content of some mineral elements in the tubers [2]. The plant biostimulants used in the experiment increased K content in tubers of all tested very early potato cultivars, especially in a cool growing season with drought periods during the potato growth. In the three years of the study, following application of biostimulants, the average K content was higher, on average, by $1.26 \text{ g} \cdot \text{kg}^{-1}$ DM compared with the average for the untreated control tubers. Bio-algeen S90 did not affect the P content in potato tubers, whereas Kelpak SL and HumiPlant caused a decrease in P content in tubers, on average, by $0.063 \text{ g} \cdot \text{kg}^{-1}$ DM compared to the untreated control tubers. In a previous study carried out in Poland, Bio-algeen S90 and Kelpak SL decreased K and Ca content in mature tubers of very early ('Volumia') and medium-early ('Irga', 'Satina', 'Silvana') cultivars, but did not affect the content of P, Mg, or Na [11]. A study carried out by other authors showed that Kelpak SL slightly increased P, Ca, and Mg content in tubers of medium-early ('Honorata', 'Tajfun') and medium-late ('Jelly') potato cultivars, whereas plant biostimulants based on peat extract GreenOk (humic substances $20 \text{ g} \cdot \text{dm}^{-3}$) and BrunatneBio Żłoto (auxin $0.06 \text{ mg} \cdot \text{dm}^{-3}$ and cytokinin $12 \text{ mg} \cdot \text{dm}^{-3}$) increased the content all of these macronutrients in the potato tubers [31]. In a study carried out in Pakistan, *A. nodosum* extract Primo increased both K and P content in tubers of the medium-early cultivar 'Sante' [14], whereas a study carried out in Korea showed that soil or foliar application of humic and fulvic acids increased K and P content in tubers of the late cultivar 'Atlantic' [21]. Later research carried out in Turkey showed that soil application of crude humic acids from leonardite in

Agro-Lig (total humic acid 85%) increased the content of K, P, Ca, and Mg in tubers of late maturity cultivar 'Caspar' [32]. Foliar or soil application of seaweed extracts caused an increase in root mass or root-to-shoot ratio in various different crops. This effect is believed to be a result of auxins or cytokinin contents in the seaweed extracts. A larger and more robust root system contributes to enhancing plant nutrient uptake [4,33]. Bio-algeen S90 increased Mg and Na content in carrot roots and, at the same time, slightly decreased the content of K and P, and distinctly reduced the content of Ca [9], whereas Kelpak SL increased both the content of Mg and Na, as well as the content of K, P, and Ca in carrot roots [10]. Humic substances, irrespective of the dose, can negatively affect plant P uptake, whereas the uptake of other minerals is not significantly affected [4], which was confirmed in the present study. Wierzbicka [34] showed a significant positive correlation between the K and P content in potato tubers, which was not confirmed in the present study. Kelpak SL and HumiPlant increased the K content in immature tubers of very early potato cultivars but, at the same time, decreased P content. In general, increased availability of P in the soil leads to an increase in this mineral content in potato tubers, but this effect was not observed for the very early cultivar 'Agata' [35]. The distribution of minerals varies greatly within the potato tuber. The concentration of P is higher in the skin than in the flesh of tubers, whereas K displays a gradient in the opposite direction. High concentrations of some minerals in the skin may reflect direct uptake from the soil across the periderm [12]. Głosek-Sobieraj et al. [13] showed that Kelpak SL increased K content and Bio-algeen S90 increased P content in the skin of tubers of medium-early potato cultivars. High concentrations of most minerals in the skin of potato tubers may reflect direct uptake from the soil across the periderm. Direct uptake of minerals into the developing tubers across the living epidermis, before the process of suberisation, is possible, although in mature tubers, it will be limited due to the suberised nature of the periderm [12].

The content of macronutrients in potato tubers is affected by cultivar, the phytoavailability of mineral elements in the soil and weather conditions [2,3,36,37]. The macronutrient contents in tubers of very early potato cultivars tested were similar, except Mg. Tubers of 'Milek' contained lower Mg than 'Denar' and 'Lord'. Wegener et al. [38] reported that K, P, and Mg content in potato tubers increased, while Ca content reduced as a result of drought stress, which was not confirmed in the present study. According to Mazurczyk and Lis [39], weather conditions during potato growth have no effect on macronutrient content in tubers. A previous study showed that the contents of Ca and Mg in the potato tubers decreased slightly along with the increase in the soil pH values, whereas the increase in soil pH values had a variable effect on the P content [40], which was not confirmed in the present study. The content of P and Mg in the early crop potato tubers decreased along with the increase in the soil pH values, whereas the content of Ca display a gradient in the opposite direction.

Nutrient uptake by plants depends on their phytoavailability in the soil and on their synergism and antagonism interaction [40,41]. There is limited information about the effect of biostimulants on the macronutrient ionic ratios in potato tubers [42]. The biostimulants used in the experiment caused an increase in the mass ratios of $K^+ : Ca^{2+}$ and $K^+ : Mg^{2+}$ in potato tubers, as a result of an increase of K content, compared to the untreated control tubers, but did not affect the mass ratios of $Na^+ : Ca^{2+}$ and $Na^+ : Mg^{2+}$. Following plant biostimulants application, the mass ratio of $(K^+ + Na^+) : (Ca^{2+} + Mg^{2+})$ in potato tubers was broader, and the mass ratio of Ca:P was similar to the untreated control tubers. An increase in the ratio of the sum of univalent cations to the sum of bivalent cations in early crop potato tubers caused a decrease in their nutritional value.

A previous study showed that the soil reaction affects the mass ratio of Ca:P in potato tubers [40,42], which was confirmed in the present study. Regardless of treatment (with or without biostimulant), the Ca:P ratio was narrowest and the $K^+ : Ca^{2+}$ and $Na^+ : Ca^{2+}$ ratios were broadest in the potato tubers from the soil with lowest pH.

According to Sawicka et al. [37], the genotypic variability plays a dominant role in the variability of macronutrient content in potato tubers. In the present study, the ionic ratios of macronutrient in tubers of the very early potato cultivars tested were similar, except the $Na^+ : Mg^{2+}$ ratio, due to a lower content of Mg in the 'Milek' tubers.

5. Conclusions

The foliar application of seaweed extracts Bio-algeen S90 (*A. nodosum*) and Kelpak SL (*E. maxima*), as well as humic and fulvic acids in HumiPlant (leonardite extract), increased K content in tubers of very early potato cultivars 75 days after planting, on average, by 1.26 g·kg⁻¹ DM compared with the untreated control tubers. Bio-algeen S90 did not affect the P content in tubers, whereas Kelpak SL and HumiPlant reduced the P content, on average, by 0.063 g·kg⁻¹ DM. The biostimulants did not affect Ca, Mg, or Na content in tubers. The use of biostimulants resulted in an increase in the mass ratios of K⁺:Ca²⁺, K⁺:Mg²⁺, and (K⁺ + Na⁺):Ca²⁺ + Mg²⁺ in very early potato cultivars, compared with the untreated control tubers, but did not affect the mass ratios of Na⁺:Ca²⁺ and Na⁺:Mg²⁺ or the mass ratio of Ca:P. The macronutrient content in early crop potato tubers and their ionic ratios depended on the cultivar and environment conditions.

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