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Effect of nitrogen and magnesium sulfate application on sugar beet yield and quality

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Abstract: Adequate nutrition of sugar beet with magnesium (Mg) and sulfur (S) has been assumed to be the key to increase fertiliser nitrogen (N) efficiency. This hypothesis was validated on two soils differing in textural class, i.e., sandy and loamy. The experiment consisted of three factors: (1) in-soil application of Kieserite (0, 24 kg Mg/ha); (2) foliar application of Epsom salt (0.2 kg Mg/ha); (3) N rates (0, 40, 80, 120, 160 and 200 kg N/ha). The following parameters were evaluated: (*i*) yield of storage roots (TY); (*ii*) qualitative features of storage roots, and (*iii*) yield of white sugar (WSY). Both yield characteristics, regardless on soil, were affected to a greater extent by in-soil than foliar MgS application. The highest increments of TY and WSY were obtained in 2016, a year with fewer favourable weather conditions and in soil with a wider Ca:Mg ratio. The greatest effect of Kieserite on TY and WSY was observed under low rates of applied N (up to 80 kg/ha). It can be concluded that the right nutrition of sugar beet with MgS in the early stages of sugar beet growth is the prerequisite of an effective N management on soils rich in mineral N.

Keywords: *Beta vulgaris* L.; Mg × N interaction; nitrogen rates; sucrose concentration

The global production of sugar in the world is about 180 mln t (USDA 2021). The share of sugar beet in the total sugar production is 20% and 50% come from the European Union (EU). The most important sugar beet growing countries in the EU in 2019 were France, Germany, Great Britain and Poland. In Poland, the area sown with sugar beet in 2019 was 242 000 ha. The yield of storage roots, averaged for 2015–2019, was 60 t/ha (GUS 2021). This yield accounts for 70–75% of the yield potential of sugar beet cultivars in Poland (COBORU 2021). The key reasons of the yield gap are not only unfavourable weather conditions during the growing season but also an inadequate balance of applied nitrogen (N) with other nutrients. Soils originated from postglacial material are naturally poor in available magnesium (Mg). Sugar beet is among the crops with high nutritional requirements for Mg (Grzebisz 2013).

Magnesium has numerous biochemical and physiological functions in plants (Senbayram et al. 2015). One of the most important is sucrose export from leaves to roots. Sugar beet plants well-nourished with Mg in the early stages of growth build-up a large root system, subsequently affecting on the efficiency of nutrient uptake from the soil solution (Hermans et al. 2005). The knowledge about the role of Mg in the control of fixation, transformation and partitioning of carbon (C) and N compounds in plants is well-recognised (Cakmak and Kirbky 2008). However, the impact of this nutrient on the yield-forming function of fertiliser N in sugar beet production is still insufficient. The newest scientific reports show that crop plants differ in response to forms and rates of the applied Mg fertilisers (Wang et al. 2020). The sugar beet response to Mg also depends on interaction with other nutrients, such as potassium, calcium, and sulfur (Gransee and Führs 2013, Orlovius and McHoul 2015).

The research problem of this work is to define to how the extent the production efficiency of the progressively increasing N rates applied to sugar beets depends on methods of magnesium sulfate application. For this purpose, the effect of Kieserite in-soil application and the in-season of Epsom salt

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to sugar beet foliage on yields of storage roots and white sugar was evaluated on two soils, differing in texture.

MATERIAL AND METHODS

Two-year field experiments were carried out in central-western Poland on two soils, differing in localisation and soil properties: (1) Nowa Wieś Królewska (52°15'27''N, 17°35'52''E); (2) Neryngowo (52°16'56''N, 17°36'52''E). In both locations, soils are classified as Albic Luvisol type (WRB 2015). The soil in the first location is classified as loamy sand, and in the second location, as a sandy loam. Both soils differed substantially in the content of plant-available nutrients. In the first test site, the content of Mg in the topsoil was low (2015) and high (2016). In the second test site, the content of Mg was medium and very high, respectively (Table 1).

The experiments were set up in a split-plot design with three factors: (1) in-soil application of 24 kg Mg/ha and 46 kg S/ha (acronym –MgS and +MgS, respectively); (2) foliar application of 2.0 kg Mg/ha and 2.6 kg S/ha (–FF and +FF); (3) six rates of N (0, 40, 80, 120, 160 and 200 kg N/ha). The number of replication was 4 with the area of a single plot of 81 m^2.

The in-soil application of Mg and S was based on Kieserite (15% Mg + 13% S), applied three weeks before sugar beet sowing. Foliage MgS application was based on Epsom salt (9.6% Mg + 13% S), applied two times, i.e., at the 6^{th} leaf stage (BBCH 16) and two weeks later. The applied rate of Mg in a single spraying was 1.0 kg/ha (5% solution of Epsom salt). Nitrogen in the form of ammonium nitrate (34%) was applied before sowing and at the BBCH 14/15 in accordance to the experiment schedule (40 + 0, 80 + 0, 80 + 40, 80 + 80, 80 + 120 kg N/ha). Basic fertilisation with phosphorus (P) and potassium (K) was carried out just before winter ploughing in the following rates: 17.4 kg P/ha (triple superphosphate, 17.4% P) and 99.6 kg K/ha (potassium chloride, 49.8% K). The fore-crop for sugar beet was winter triticale. The Telimena cultivar of *Beta vulgaris* L. was sown on April 10 to 12, assuming a plant density of 106 000/ha.

The yield of storage roots (TY) was determined manually from the area of 10 m^2. The standard quality characteristics of storage roots were determined in a laboratory of the Pfeifer & Langen Company in Środa Wielkopolska, Poland, using the Venema automatic beet laboratory system (Type IIIG). Samples of beets were first washed; next sugar beet brei was

Table 1. Soil proportion depending on the year and location of the experience

Soil layer (cm)	Clay content (%)	pH[1]	N_{min}[2] (kg/ha)	P[3]	K[3]	Mg[3]	Ca[3]
				(mg/kg)			
Location 1, 2015							
0–30	3	5.5	35.1	149.0^{M}	140.9^{M}	40.7^{L}	886.2
30–60	6	5.6	43.6	52.1	128.5	108.1	1 145.8
60–90	7	6.1	39.8	18.0	124.1	157.6	1 585.0
Location 1, 2016							
0–30	3	5.8	42.6	135.7^{M}	214.4^{VH}	78.4^{H}	840.0
30–60	7	6.4	65.5	78.3	131.7	95.6	1 176.4
60–90	10	7.3	47.1	12.5	91.8	122.3	1 987.4
Location 2, 2015							
0–30	6	6.5	57.5	126.3^{M}	253.9^{VH}	90.9^{M}	800.4
30–60	11	6.7	62.4	84.8	126.2	91.9	1 115.1
60–90	12	7.5	42.8	9.7	66.4	124.6	2 002.6
Location 2, 2016							
0–30	7	6.8	56.6	154.4^{VH}	317.3^{VH}	115.9^{H}	2 580.0
30–60	9	6.7	34.3	98.1	206.6	98.0	2 128.1
60–90	13	7.0	51.8	15.1	130.8	111.3	2 138.6

[1]1 mol/L KCl; [2]sum of N mineral (N_{min}) forms extracted in 0.01 mol/L $CaCl_2$; [3]Mehlich 3 method. Ranges (Kęsik et al. 2015): VH – very high; H – high; M – good; L – low

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Tabel 2. Selyaninov's hydrothermal coefficients during field experiments

Year	Month						
	IV	V	VI	VII	VIII	IX	X
2015	1.76	0.85	1.15	1.26	0.82	0.75	1.37
2016	0.87	0.52	0.93	1.95	0.52	0.27	3.01

Classification of droughts based on the Selyaninov's hydrothermal coefficient: > 2.0 – immoderately humid; 1.0–2.0 – humidity is sufficient; 1.0–0.7 – insufficient humidity (dry); 0.7–0.4 – very dry

prepared and clarified with 0.3% $Al_2(SO_4)_3$ solution. In the extract obtained, the following set of characteristics was determined: sucrose concentration in beet fresh matter by polarimetric method (SC), K and Na concentrations by flame photometry, and α-amino nitrogen (AmN) by a fluorometric method, using ortho-phthaldialdehyde. Standard sugar losses to molasses (SML), the content of white sugar (WSC) and white sugar yield (WSY) were calculated according to Buchholz et al. (1995).

In order to assess the influence of experimental factors on sugar beet yield, qualitative features and parameters of storage roots and finally yield of white sugar, the three-way ANOVA was applied for each year and four-way ANOVA for evaluating the interaction of years with trial factors. All statistical analyses were carried out separately for each of the study site. Means were separated by the honest significant difference (*HSD*) using the Tukey's method when the *F*-test indicated significant factorial effects at the level of $P < 0.05$. The curvilinear regression was used to calculate the relationship between N rates and white sugar yield. Statistica 13 software (TIBCO Software Inc., Palo Alto, USA) was used for all statistical analyses.

RESULTS AND DISCUSSION

The yield of storage roots on sandy soil in both years was similar, averaging 63.6 t/ha. On loamy soil, it was much higher, reaching on average 81.5 t/ha, and depended on the growing season. In 2015, TY was

Table 3. Response of sugar beet yield to experimental factors (t/ha)

	Location 1			Location 2		
	2015	2016	mean	2015	2016	mean
Kieserite						
–MgS	61.9	61.8	61.9	84.5	74.0^{b}	79.3^{b}
+MgS	64.2	66.4	65.3	85.5	81.8^{a}	83.7^{a}
$F_{1,72}/F_{1,144}$	ns	ns	ns	ns	4.49*	4.62**
Epsom salt						
–FF	62.7	64.4	63.6	85.7	77.8	81.8
+FF	63.4	63.7	63.5	84.3	78.0	81.2
$F_{1,72}/F_{1,144}$	ns	ns	ns	ns	ns	ns
Nitrogen rates						
0	60.0	56.3^{b}	58.1^{b}	80.4^{b}	63.5^{b}	72.2^{b}
40	64.2	59.7^{ab}	62.0^{ab}	87.5^{ab}	78.8^{ab}	82.5^{ab}
80	66.8	65.9^{ab}	66.3^{ab}	90.2^{a}	78.7^{ab}	84.5^{a}
120	67.3	68.6^{a}	68.0^{a}	85.5^{ab}	84.0^{a}	84.7^{a}
160	63.4	65.6^{ab}	64.5^{ab}	83.9^{ab}	80.2^{ab}	82.1^{ab}
200	56.6	68.3^{ab}	62.5^{ab}	82.7^{ab}	82.3^{a}	82.5^{ab}
$F_{5,72}/F_{5,144}$	ns	2.45*	2.44*	2.39*	2.67*	3.61**

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$. Different letters indicate statistically significant differences between treatments. ns – not significant

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higher by 9.1% compared to 2016 (85 *vs.* 77.9 t/ha). Sugar beet requires 600 to 800 mm of precipitation for the realisation of its yielding potential in the temperate zone (Kenter et al. 2006). In our studies, the sum of precipitation was much lower, amounting to 542 mm and 510 mm, respectively. Simultaneously, coefficients of hydrothermal plant protection in the growing season were higher in 2015 than in 2016 (Table 2). These differences indicate better water management by sugar beets grown on loamy than on sandy soil (Table 3).

The highest impact on TY among the fertilisation factors was exerted by N (Table 3). The results corroborate the dominant role of N in sugar beet production (Hergert 2010). Sugar beets on sandy soil in both years reached the highest TY on the plot fertilised with 120 kg N/ha. The net increase compared to the control (without N) was 12.2% in 2015 and 21.9% in 2016. A different trend was recorded on loamy soil. In 2015, TY increased up to 80 kg N/ha and in 2016 to 120 kg N/ha. Compared to the control, the net TY increase was 12.3% and 32.4%, respectively.

According to Märländer et al. (2003), the total N supply from soil and applied fertilisers necessary to reach the maximum yield of storage roots is 240 kg/ha. In our study, the content of N_{min} was high. Therefore, N rates of 160 and 240 kg/ha were not productive, leading to a significant increase in the content of AmN in storage roots. Taking into account the parameter of SML (sugar losses to molasses), a safe N rate to reach the high quality of storage roots should not exceed 80 kg/ha. This effect was statistically corroborated on sandy soil (Table 4). However, a positive trend in TY to the increasing N rates was observed for plants fertilised with Kieserite. The difference between –MgS and +MgS treatments was 3.7% and 7.4% in 2015 and 2016, respectively (Table 3). On loamy soil, the significant TY increase in response to Kieserite was recorded only in 2016 (+10.5%).

According to Hoffmann et al. (2004), a risk of S deficiency in sugar beets is low. Hence, it is assumed

Table 4. Characteristics and parameters of storage roots quality – site 1

	SC (%)	AmN (mmol/kg)	K (mmol/kg)	Na (mmol/kg)	SML (%)	WSC (%)	WSY (t/ha)
Year							
2015	21.06^{b}	23.46^{a}	43.06^{a}	1.17^{b}	2.40^{a}	18.67^{a}	11.8^{a}
2016	16.27^{a}	10.08^{b}	36.99^{b}	3.38^{a}	2.01^{b}	14.26^{b}	9.1^{b}
$F_{1,144}$	2 949***	490**	54.9***	620***	319***	2 440***	69.9***
Kieserite							
–MgS	18.67	16.77	40.16	2.26	2.21	16.46	10.2
+MgS	18.67	16.78	39.89	2.29	2.20	16.46	10.8
$F_{1,144}$	ns	ns	ns	ns	ns	ns	ns
Epsom salt							
–FF	18.54^{b}	17.79^{a}	40.87^{a}	2.35	2.24^{a}	16.30^{b}	10.4
+FF	18.79^{a}	15.76^{b}	39.19^{b}	2.20	2.16^{b}	16.63^{a}	10.6
$F_{1,144}$	8.1**	11.3***	4.1*	ns	13.5***	13.8***	ns
Nitrogen rates							
0	18.96^{a}	12.97^{d}	39.35	2.43	2.10^{c}	16.86^{a}	9.9
40	18.82^{ab}	13.39^{d}	40.56	2.30	2.13^{c}	16.69^{ab}	10.4
80	18.82^{ab}	15.58^{cd}	38.82	2.32	2.15^{bc}	16.67^{ab}	11.1
120	18.63^{abc}	17.19^{bc}	41.77	2.10	2.24^{ab}	16.39^{bc}	11.1
160	18.45^{ac}	20.10^{ab}	39.96	2.12	2.28^{ab}	16.17^{c}	10.4
200	18.31^{c}	21.42^{a}	39.71	2.40	2.31^{a}	16.00^{c}	9.9
$F_{5,144}$	5.4*	22.0***	ns	ns	10.4***	9.4***	ns

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$. Different letters indicate statistically significant differences between treatments. SC – sucrose concentration; AmN – α-amino nitrogen; SML – standard sugar losses to molasses; WSC – content of white sugar; WSY – white sugar yield; ns – not significant

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that the main reason of the variable response of this crop to Kieserite application is the content of plant-available Mg in the soil (Grzebisz 2013, Orlovius and McHoul 2015). The results of this study did not give a clear answer on the impact of the level of soil Mg on TY and WSY. The highest TY and white sugar yield (WSY) increase in response to the applied Kieserite was recorded on loamy soil, in which the content of available Mg was higher with respect to the sandy one. The reason for the observed phenomenon might be the wider ratio of Ca^{2+} to Mg^{2+}, or Mg^{2+} to K^+ (Table 1). These cations compete with each other both during the uptake by roots and transport within the plant (Gransee and Führs 2013). The analysis of the nutritional status of sugar beet, using the compositional nutrient diagnosis (CND), showed that only a balanced supply of all required nutrients to sugar beet is a guarantee of high yield (Barłóg 2016). Regardless on the soil textural class, the highest TY increase in response to Kieserite application was recorded in 2016, which was drier than in 2015 (Table 2). In can be assumed that in this particular year, maintaining an adequate supply of Mg to roots of sugar beet required, therefore, a higher concentration of Mg^{2+} cations in the soil solution (Gransee and Führs 2013).

The foliar method of sugar beet fertilisation with MgS did not influence the TY of storage roots. There are, however, some reports, indicating a positive impact of foliar application of the Epsom salt on TY and technological quality of sugar beets (Barłóg and Grzebisz 2001). In our study, the in-season application of MgS reduced, regardless of soil texture, the content of AmN and K in storage roots (Tables 4 and 5).

The average difference in WSY in response to –MgS and +MgS variants was almost the same for both soil, reaching 5.9% and 6.0%, respectively. The recorded increase was significant but only for loamy soil. No significant interaction between experimental factors, i.e., Kieserite × N rate, was obtained. Nevertheless, a significantly higher productivity of N was observed but provided lower its rate and simultaneous ap-

Table 5. Characteristics and parameters of storage roots quality – site 2

	SC (%)	AmN	K	Na	SML	WSC	WSY (t/ha)
		(mmol/kg)			(%)		
Year							
2015	17.75^{a}	21.56^{a}	46.04^{b}	3.68^{b}	2.45^{a}	15.30^{a}	13.0^{a}
2016	16.18^{b}	15.60^{b}	48.26^{a}	4.45^{a}	2.35^{b}	13.82^{b}	10.9^{b}
$F_{1,144}$	411***	57.1***	5.1*	31.0***	9.7**	258***	43.7***
Kieserite							
–MgS	16.9	19.53^{a}	47.7	4.09	2.43^{a}	14.48	11.6^{b}
+MgS	17.0	17.63^{b}	46.6	4.04	2.37^{b}	14.64	12.3^{a}
$F_{1,144}$	ns	5.7*	ns	ns	4.6*	ns	4.3*
Epsom salt							
–FF	16.94	19.63^{a}	48.97^{a}	4.01	2.45^{a}	14.48	11.9
+FF	16.99	17.53^{b}	45.33^{b}	4.12	2.34^{b}	14.65	12.0
$F_{1,144}$	ns	7.0**	14.3***	ns	13.8***	ns	ns
Nitrogen rates							
0	17.22^{a}	14.14^{d}	48.38	4.33	2.32^{b}	14.90^{b}	11.1
40	17.04^{abc}	15.80^{cd}	48.19	4.25	2.35^{b}	14.69^{ab}	12.3
80	17.08^{ab}	17.31^{cd}	48.31	3.80	2.38^{ab}	14.70^{ab}	12.5
120	16.96^{abc}	18.82^{bc}	44.92	4.15	2.37^{a}	14.60^{abc}	12.4
160	16.78^{bc}	21.83^{ab}	45.34	4.04	2.45^{ab}	14.34^{ac}	11.8
200	16.69^{c}	23.57^{a}	47.74	3.83	2.52^{a}	14.16^{c}	11.7
$F_{5,144}$	4.3**	13.8***	ns	ns	4.2**	5.6***	ns

*P < 0.05; **P < 0.01; ***P < 0.001. Different letters indicate statistically significant differences between treatments. SC – sucrose concentration; AmN – α-amino nitrogen; SML – standard sugar losses to molasses; WSC – content of white sugar; WSY – white sugar yield; ns – not significant

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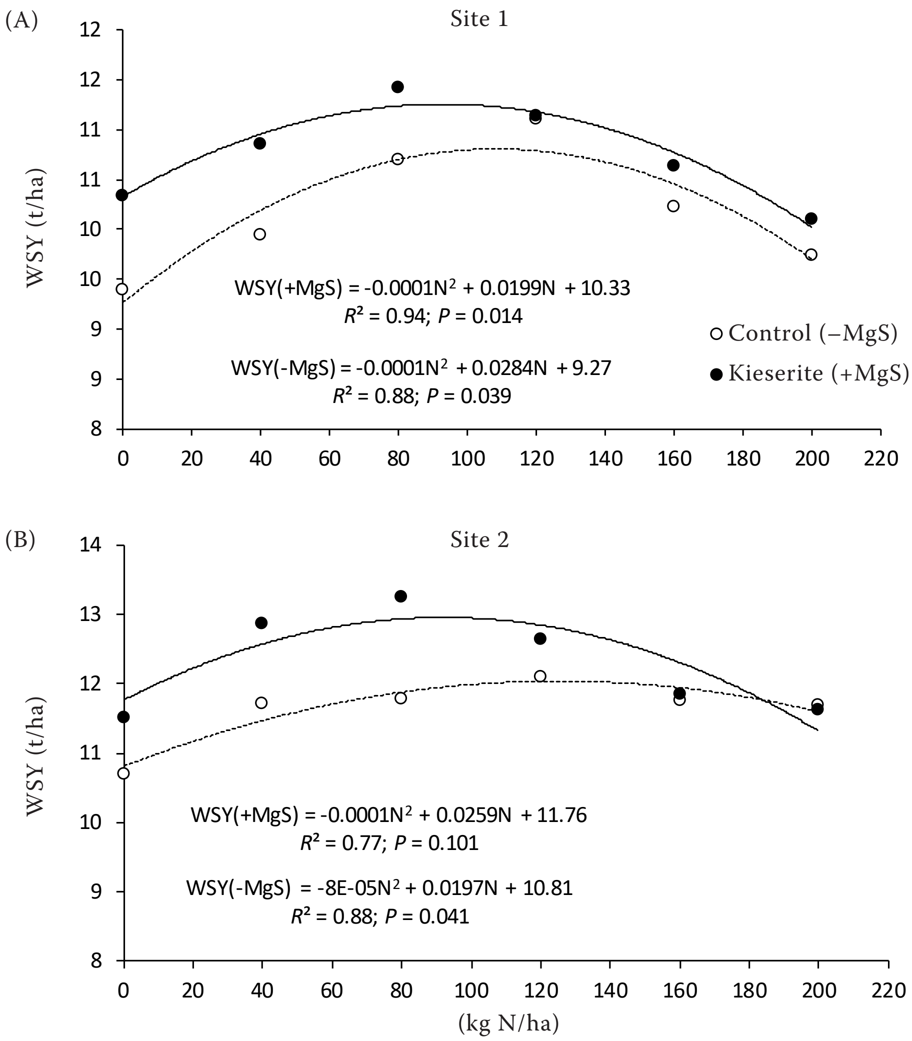

Figure 1. White sugar yield (WSY) as a function of N-rates depending on the location and Kieserite (MgS) application

plication of Kieserite (Figure 1). It was concluded that MgS application resulted in a lesser requirement of sugar beet for fertiliser N. On sandy soil, the optimal N rate provided MgS application was 92.8 kg/ha, whereas, without MgS, it was by 15.4 kg/ha higher (108.2). On loamy soil, the greater difference was observed, which was 92.1 and 125.1 kg N/ha, respectively. According to Grzebisz (2013), at low N rates, higher Mg^{2+} concentration in the soil solution stimulates the uptake of nitrates, which subsequently increases the growth rate of sugar beet in the early stages and is a prerequisite for higher yields, both TY and WSY.

As results from the study, the sugar beet yield depended to a greater extent on in-soil than on foliar application of magnesium sulfate. This way of MgS management clearly stresses the important role of both nutrients in the early stages of sugar beet growth. The study clearly shows that in fields with the high content of N_{min} in the soil, the application of 24 kg Mg/ha reduced the optimal N rate for the maximum WSY. Foliar application of MgS to sugar beet, in spite of improvement of storage roots technological quality, did not affect white sugar yield.

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