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# Impact of winter oilseed rape nutritional status during vegetative growth on yield

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**Abstract**: The nutritional status of winter oilseed rape (WOSR) during its vegetative period is crucial for plant growth and can be used for the seed yield prediction. This hypothesis was verified based on the data from long-term field experiments. The experiment consisted of four potassium (K) treatments based on the progressive K supply potential to plants from soil and fertilizer and two magnesium treatments (–Mg, +Mg) conducted in 2013–2015. The content of nutrients ($N_{tot}$, P, K, Mg, Ca, Fe, Mn, Zn, Cu) was determined at the rosette stage (BBCH 30) for leaves and separately for leaves and stems in the late stage of inflorescence growth (BBCH 57–59). The low K content appeared as the key limiting nutrient in WOSR plants in the rosette stage due to the insufficient soil fertility level, depended even more on weather conditions. This negative K nutritional trait persisted through the whole vegetative WOSR growth. Its detection was possible, because stems were included in the diagnostic procedure. The most reliable prognosis of WOSR yield was conducted based on the nutritional status of stems in the late stage of the inflorescence development.

**Keywords**: *Brassica napus* L.; macronutrient; fertilization; drought; potassium deficiency

The key nutritional factor, driving winter oilseed rape (WOSR) yield is nitrogen (N) (Schulte auf'm Erley et al. 2011). The study focus on total nitrogen ($N_{tot}$) can only prove successful, provided $N_{tot}$ is well balanced with other nutrients, like phosphorus (P), potassium (K). As recently reported by Grzebisz et al. (2018), the effective use of P by WOSR requires a good supply of K, which is responsible for the number of seeds produced by the crop. The key physiological functions of K, including its drought ameliorating effect, are well recognized (Römheld and Kirkby 2010). The consumption of K fertilizers, even in leading WOSR producers, is low. The annual consumption of K fertilizers in 2008–2016 was 27.0 ± 6.0 kg/ha for Germany, 8.2 ± 2.8 kg/ha for Czech Republic, and 32.9 ± 4.5 kg K/ha for Poland (FAOSTAT 2019). The study in China clearly showed that insufficient input of K to WOSR both from soil or fertilizers seriously limits the yield (Ren et al. 2013).

The key sensitive stages of yield development during the spring vegetation of WOSR are rosette (BBCH 30) and inflorescence emergence (BBCH 50–59). During the first stadium, the potential number of primary branches is fixed. The nutrient imbalance as recorded at this stage leads to the yield decline. The final number of flowers and pods is fixed just before flowering. It also depends on the supply of N, which should be in a balance with other nutrients like K (Szczepaniak 2014, Weyman et al. 2015).

It has been assumed that the sensitivity of WOSR to K supply will be best evaluated in the long-term experiment with K, in which the soil K fertility is highly differentiated. The key objective of the study was to predict the seed yield of WOSR based on nutrients content in its vegetative tissues in two cardinal stages of the yield formation, i.e. the rosette (BBCH 30) and the final phase of inflorescence growth (BBCH 57–59).

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## MATERIAL AND METHODS

Field trials with WOSR were carried out between 2013–2015 at the Brody Experimental Farm (Poznan University of Life Sciences, 52°44'N, 16°28'E), Poland. The study based on the experimental long-term trial, which was established in 1991 on Albic Luvisol originated from loamy sand. The content of available nutrients, measured each year before sowing, ranged for P from 168 to 193 mg/kg soil; for K, its content depended on the treatment and ranged: K0 → 101–129; K1 → 122–146; K2 → 136–159; K3 → 152–186 mg/kg soil; for Mg, it ranged from 48 to 64 mg/kg soil (Mehlich 1984). The amount of mineral nitrogen ($N_{min}$) measured in spring in the layer of 0–90 cm ranged from 64 to 82 kg/ha (0.01 mol/L $CaCl_2$). Soil pH was 6.3–6.7 (1.0 mol/L KCl). Meteorological data are shown in Figure 1.

The field trial arranged as a two-factorial split-block design, replicated four times, comprised of two systems of nutrient application:

- four rates of potassium: K0 → 0; K1 → 49.8; K2 → 99.6; K3 → 199.2 kg K/ha.
- two rates of magnesium: 0, 15 + 3 kg Mg/ha.

The experiment had a randomized block design, with four replicates. The area of an individual plot was 22.4 m² (2.8 m × 8 m). The fore-crop for WOSR was faba bean. Seeds of WOSR line covariate Nectar ES were sown each year at a rate of 50 plants/m² at 24, 20, 25 August, 2012, 2013, 2014. Rates and forms of nutrients applied two weeks before WOSR sowing were as follows: (i) K as KCl and (ii) Mg as Kieserite – in accordance to the experimental design (iii) P in the rate of 26.2 kg/ha as TP (triple superphosphate). Mg applied to WOSR foliage at BBCH 30 was in the form $MgSO_4{\cdot}7\ H_2O$. N as $NH_4NO_3$ (34%) was applied in the double rate of 80 kg/ha at the beginning of spring vegetation and repeated at BBCH 29. WOSR was harvested from an area of 12 m² at 20, 22, 15 July 2013, 2014, 2015, respectively. Seed yield was adjusted to 8% moisture content.

Plant material for the determination of dry matter and nutrients content was collected from an area of 0.2 m² at plant stage of BBCH 30 (5.04, 27.03, 6.04) and 57–59 (29.04, 4.05, 2.05 in 2013, 2014, 2015, respectively). At the latter stage, it was divided into leaves and stems. The biomass of plants at BBCH 30 was in the range of 1.2–1.5, 0.9–1.1, 1.5–2.0 t/ha dry matter (DM) and at BBCH 57–59 of 3.1–3.0, 5.0–5.5, 5.0–6.0 t/ha DM, in 2013, 2014, 2015, respectively. $N_{tot}$ content was determined using a standard macro-Kjeldahl procedure. For other nutrients, the harvested plant sample was dried at 65°C and then mineralized at 600°C. The obtained ash was then dissolved in 33% $HNO_3$. The P concentration was measured by the vanadium-molybdenum method using a Specord 2XX/40 (Analytik Jena, Jena, Germany) at a wavelength of 436 nm. K concentration was measured by the flame-photometry and other nutrients by atomic-absorption spectrometry – flame type.

The obtained data were subjected to the analysis of variance (Statistica 10, StatSoft. Inc., Tulsa, USA), and the differences between treatments were evaluated with Tukey's test. The simple and stepwise regression was applied to define the optimal set of variables for the plant characteristics. The best regression model was selected based on the highest *F*-value for the entire model.

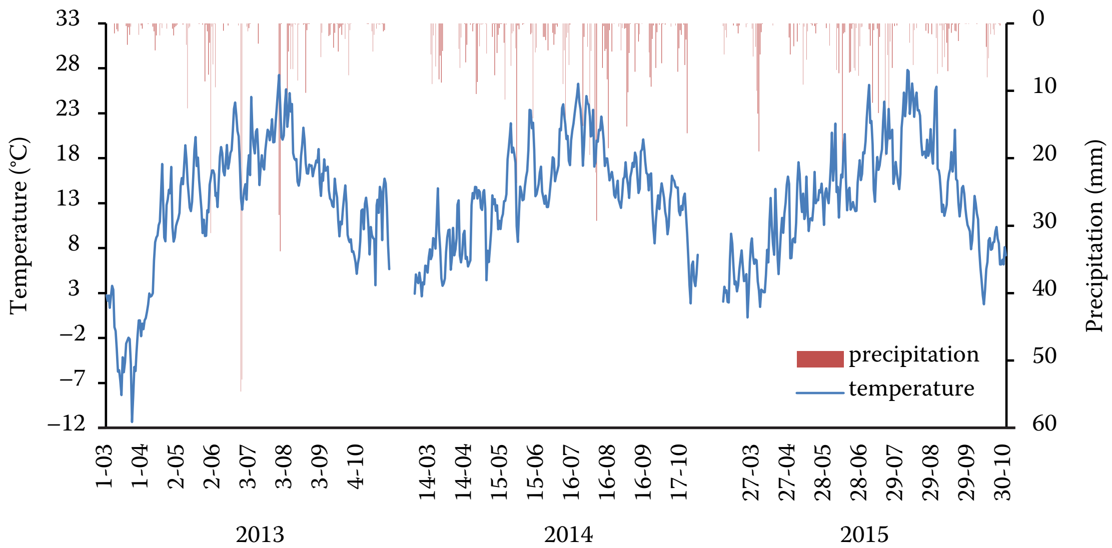


Figure 1. Daily mean air temperature and total precipitation at the Brody Experimental (Poznan, Poland)

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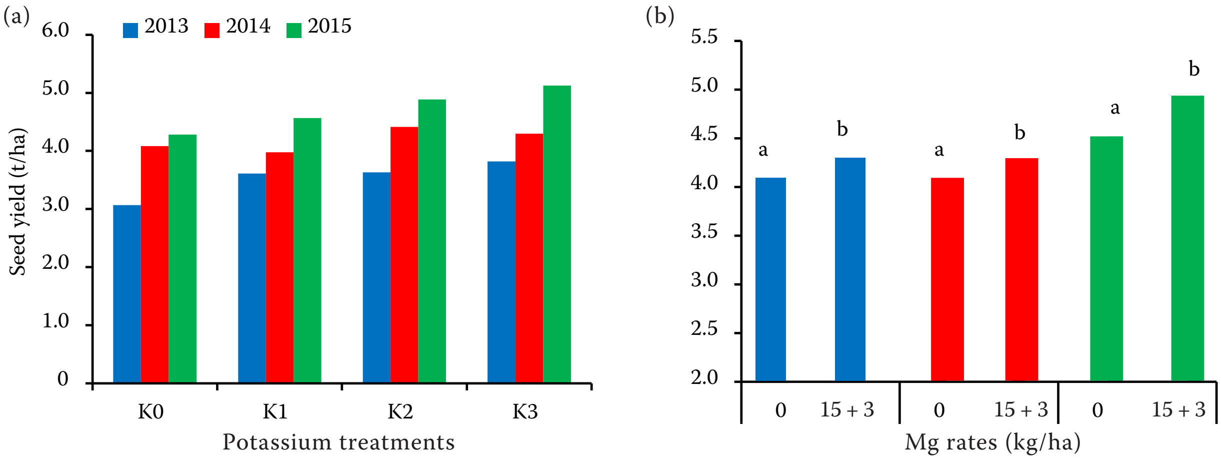


Figure 2. Effect of (a) potassium and (b) magnesium fertilization on seed yield of winter oilseed rape in consecutive years of study. K0 – 0, K1 – 49.8, K2 – 99.6; K3 – 199.2 kg K/ha

## RESULTS AND DISCUSSION

Yields of WOSR significantly depended on the interaction of years and K treatments (Figure 2a). The low yield in 2013 was due to frost, which took place between 19th and 23rd March. Total sum of rainfalls in March and April amounted to 27.2 mm (1/3 of the long-term average) (Figure 1). In this particular year, the shortage of K input resulted in yield decrease by 0.6 t/ha (–15%) with respect to the NP control. The yield increase due to K fertilization can be explained by the increased frost resistance of plants well supplied with this nutrient (Römheld and Kirkby 2010). In 2014, the average yield was above 4 t/ha, but the effect of K was non-consistent. The amount of rainfalls in these two critical months was 125% of the long-term average. In 2015, yield harvested on the NP control was at the level of

Table 1. Nutrient content in leaves of winter oilseed rape at the rosette stage (BBCH 30)

| Factor | Level of factor | $N_{tot}$ | P | K | Mg | Ca | Fe | Mn | Zn | Cu |
|---|---|---|---|---|---|---|---|---|---|---|
| | | (g/kg DM) | | | | | (mg/kg DM) | | | |
| Year (Y) | 2013 | 42.8$^{b}$ | 2.1$^{a}$ | 32.8$^{a}$ | 2.7$^{c}$ | 15.4$^{b}$ | 217.2$^{a}$ | 43.5$^{c}$ | 38.7$^{c}$ | 6.0$^{c}$ |
| | 2014 | 37.8$^{a}$ | 2.6$^{b}$ | 37.7$^{b}$ | 2.1$^{b}$ | 15.3$^{b}$ | 193.8$^{a}$ | 36.8$^{b}$ | 19.7$^{b}$ | 4.3$^{b}$ |
| | 2015 | 38.1$^{a}$ | 3.9$^{c}$ | 48.6$^{c}$ | 1.7$^{a}$ | 13.6$^{a}$ | 336.0$^{b}$ | 26.1$^{a}$ | 17.1$^{a}$ | 2.8$^{a}$ |
| *F*-value | | 40.0*** | 375.1*** | 201.5*** | 54.3*** | 4.4* | 48.5*** | 74.0*** | 279.0*** | 157.0*** |
| Potassium rate (kg K/ha) (K) | 0.0 | 37.8$^{a}$ | 2.9 | 37.7$^{a}$ | 2.2 | 14.8 | 250.9 | 35.9 | 25.3 | 4.2 |
| | 49.8 | 39.7$^{a}$ | 2.9 | 40.1$^{ab}$ | 2.1 | 14.4 | 234.7 | 37.1 | 25.9 | 4.5 |
| | 99.6 | 39.1$^{a}$ | 2.8 | 39.8$^{ab}$ | 2.2 | 14.9 | 244.8 | 34.3 | 24.4 | 4.2 |
| | 199.2 | 41.7$^{b}$ | 2.8 | 41.0$^{b}$ | 2.2 | 15.0 | 265.5 | 34.5 | 25.1 | 4.5 |
| *F*-value | | 9.9*** | 0.6 | 4.5** | 0.4 | 0.2 | 0.4 | 1.2 | 0.5 | 1.4 |
| Magnesium rate kg/ha (Mg) | 0.0 | 39.4 | 2.8 | 38.6 | 2.1 | 13.7$^{a}$ | 279.8$^{b}$ | 35.6 | 24.8 | 4.2 |
| | 15 + 3 | 39.8 | 2.9 | 40.8$^{b}$ | 2.2 | 15.8$^{b}$ | 218.1$^{a}$ | 35.3 | 25.6 | 4.5 |
| *F*-value | | 0.8 | 0.3 | 11.4** | 0.9 | 13.7*** | 23.8*** | 0.1 | 1.0 | 3.8 |
| ***F*-value for interactions** | | | | | | | | | | |
| Y × K | | 4.1** | 1.8 | 3.7** | 2.0 | 0.5 | 4.7*** | 0.8 | 1.7 | 0.9 |
| Y × Mg | | 1.6 | 4.8* | 9.5*** | 0.0 | 6.9** | 12.7*** | 3.9* | 3.0 | 2.4 |
| K × Mg | | 0.7 | 0.1 | 1.4 | 0.6 | 1.2 | 3.0* | 2.4 | 1.2 | 0.4 |
| Y × K × Mg | | 0.9 | 2.2 | 2.7* | 0.5 | 1.2 | 1.0 | 0.6 | 2.6* | 0.4 |

*$P$ < 0.05; **$P$ < 0.01; ***$P$ < 0.001; the same letter indicates a lack of significant differences within the treatment. $N_{tot}$ – total nitrogen; DM – dry matter

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Table 2. Correlation matrix between nutrients content in winter oilseed rape leaves at BBCH 30 and seed yield, $n$ = 24

| | $N_{tot}$ | P | K | Mg | Ca | Fe | Mn | Zn | Cu |
|---|---|---|---|---|---|---|---|---|---|
| Yield | –0.37 | 0.79*** | 0.89*** | –0.81*** | –0.14 | 0.31 | –0.84*** | –0.78*** | –0.78*** |
| $N_{tot}$ | 1.00 | –0.52* | –0.38 | 0.58** | 0.34 | –0.12 | 0.52** | 0.74*** | 0.71*** |
| P | | 1.00 | 0.92*** | –0.84*** | –0.31 | 0.53** | –0.93*** | –0.76*** | –0.90*** |
| K | | | 1.00 | –0.83*** | –0.18 | 0.38 | –0.90*** | –0.71*** | –0.81*** |
| Mg | | | | 1.00 | 0.38 | –0.47* | 0.81*** | 0.84*** | 0.89*** |
| Ca | | | | | 1.00 | –0.69*** | 0.25 | 0.30 | 0.47* |
| Fe | | | | | | 1.00 | –0.44* | –0.31 | –0.57** |
| Mn | | | | | | | 1.00 | 0.82*** | 0.88*** |
| Zn | | | | | | | | 1.00 | 0.90*** |

***$P$ < 0.001; **$P$ < 0.01; *$P$ < 0.05; $N_{tot}$ – total nitrogen

that in 2014 and increased in accordance with rising K input. The effect of Mg was year specific, rising from 0.2 t/ha in 2013 and 2014 to 0.38 t/ha in 2015 (Figure 2b).

The content of nutrients in WOSR rosette showed sensitivity to weather (Table 1). With respect to this factor, two key trends can be distinguished. The decreasing yearly trends in accordance with the experiment course, were observed for $N_{tot}$, K, Mg, Mn, Zn and Cu. The reversed trend was noticed for P and Fe. The significant effect of K was recorded for $N_{tot}$ and K. The highest content of both nutrients was recorded for the K3 plot. These results corroborates the hypothesis by Marschnert et al. (1997), who stated that an efficient uptake of N by plants from soil is guaranteed, provided a good supply of K is maintained. Plants fertilized with Mg showed a significantly higher content of K, Ca, and Fe.

Table 3. Nutrient content in leaves of winter oil seed rape at the stage of inflorescence development (BBCH 57–59)

| Factor | Level of factor | $N_{tot}$ (g/kg DM) | P | K | Mg | Ca | Fe (mg/kg DM) | Mn | Zn | Cu |
|---|---|---|---|---|---|---|---|---|---|---|
| Year (Y) | 2013 | 31.4$^b$ | 2.0$^a$ | 34.7$^a$ | 2.0$^b$ | 15.4 | 64.9$^a$ | 38.2$^a$ | 29.7$^a$ | 6.0$^b$ |
| | 2014 | 28.3$^a$ | 2.2$^a$ | 34.3$^a$ | 1.7$^a$ | 14.9 | 68.1$^a$ | 37.6$^a$ | 40.1$^c$ | 4.7$^a$ |
| | 2015 | 37.2$^c$ | 3.8$^b$ | 44.2$^b$ | 2.4$^c$ | 14.4 | 103.1$^b$ | 48.8$^b$ | 33.9$^b$ | 5.0$^a$ |
| *F*-value | | 120.9*** | 548.2*** | 43.2*** | 71.2*** | 2.8 | 93.6*** | 31.9*** | 37.8*** | 23.6*** |
| Potassium rate (kg/ha) (K) | 0.0 | 30.1$^a$ | 2.8$^b$ | 36.4 | 2.0$^a$ | 14.9 | 77.1 | 40.6 | 34.4$^b$ | 5.2 |
| | 49.8 | 32.1$^{ab}$ | 2.6$^a$ | 38.7 | 2.0$^a$ | 14.6 | 78.3 | 40.4 | 32.1$^a$ | 5.4 |
| | 99.6 | 33.3$^b$ | 2.6$^a$ | 36.4 | 2.0$^a$ | 14.8 | 78.6 | 41.1 | 35.4$^b$ | 5.1 |
| | 199.2 | 33.7$^b$ | 2.6$^a$ | 39.5 | 2.2$^b$ | 15.3 | 80.9 | 44.0 | 36.4$^c$ | 5.3 |
| *F*-value | | 12.0*** | 2.8* | 2.6 | 3.4* | 0.7 | 0.4 | 1.7 | 3.5* | 0.8 |
| Magnesium rate (kg/ha) (Mg) | 0 | 32.3 | 2.6 | 36.2$^a$ | 2.0 | 14.7 | 75.8$^a$ | 41.2 | 34.9 | 5.1 |
| | 15 + 3 | 32.4 | 2.7 | 39.3$^b$ | 2.1 | 15.1 | 81.6$^b$ | 41.9 | 34.2 | 5.4 |
| *F*-value | | 0.1 | 1.4 | 9.5** | 1.3 | 1.1 | 5.2* | 0.3 | 0.6 | 3.4 |
| ***F*-values for interaction** | | | | | | | | | | |
| Y × K | | 15.8*** | 1.2 | 1.2 | 0.3 | 1.1 | 1.2 | 2.3* | 1.3 | 1.5 |
| Y × Mg | | 7.3** | 3.3* | 4.8* | 0.4 | 1.1 | 0.9 | 1.3 | 4.0* | 4.4* |
| K × Mg | | 5.9** | 1.0 | 2.4 | 0.8 | 1.4 | 0.8 | 0.6 | 1.6 | 2.4 |
| Y × K × Mg | | 3.6** | 2.3* | 1.2 | 3.6** | 1.0 | 0.8 | 1.7 | 0.8 | 1.0 |

*$P$ < 0.05; **$P$ < 0.01; ***$P$ < 0.001; the same letter indicates a lack of significant differences within the treatment. $N_{tot}$ – total nitrogen; DM – dry matter

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Table 4. Correlation matrix between nutrients in winter oilseed rape leaves at the inflorescence development, and seed yield, $n$ = 24

| | $N_{tot}$ | P | K | Mg | Ca | Fe | Mn | Zn | Cu |
|---|---|---|---|---|---|---|---|---|---|
| Yield | 0.42* | 0.71*** | 0.65** | 0.46* | –0.29 | 0.78*** | 0.68*** | 0.35 | –0.51* |
| $N_{tot}$ | 1.00 | 0.66*** | 0.59** | 0.76*** | –0.03 | 0.66** | 0.60** | –0.10 | 0.25 |
| P | | 1.00 | 0.81*** | 0.78*** | –0.35 | 0.94*** | 0.78*** | –0.05 | –0.27 |
| K | | | 1.00 | 0.77*** | –0.22 | 0.82*** | 0.76*** | –0.11 | –0.15 |
| Mg | | | | 1.00 | –0.01 | 0.78*** | 0.77*** | –0.31 | 0.19 |
| Ca | | | | | 1.00 | –0.19 | –0.19 | –0.05 | 0.57** |
| Fe | | | | | | 1.00 | 0.80*** | 0.01 | –0.19 |
| Mn | | | | | | | 1.00 | –0.03 | –0.17 |
| Zn | | | | | | | | 1.00 | –0.51* |

*$P$ < 0.05; **$P$ < 0.01; ***$P$ < 0.001; $N_{tot}$ – total nitrogen

The K content in WOSR at the rosette stage appeared as the key nutritional factor, limiting the seed yield (Table 2). The step-wise analysis clearly showed that the K content explained 82% variability in the yield (Y):

$$Y = -0.0019K^2 + 0.334K - 2.005 \text{ for } n = 24, R^2 = 0.82 \text{ and } P \leq 0.001.$$

The highest yield of 5.2 t/ha can be obtained, provided K content in leaves is 61.6 g/kg DM. It is necessary to stress that K content in WOSR leaves was significantly correlated with P, but negatively with most nutrients, including Mg.

In comparison to the rosette stage, trends of nutrient contents in WOSR leaves at the end of inflorescence development were nutrient specific (Table 3). The content decrease with respect to the rosette stage was observed for $N_{tot}$ and Fe. In contrast, the contents of P, K, and Ca did not show any remarkable changes, keep-

Table 5. Nutrient content in stems of winter oil-seed rape at the stage of inflorescence development (BBCH 57–59)

| Factor | Level of factor | $N_{tot}$ | P | K | Mg | Ca | Fe | Mn | Zn | Cu |
|---|---|---|---|---|---|---|---|---|---|---|
| | | (g/kg DM) | | | | | (g/kg DM) | | | |
| Year (Y) | 2013 | 32.2$^b$ | 2.0$^a$ | 30.9$^a$ | 1.8$^a$ | 13.6$^b$ | 160.2$^b$ | 23.8$^b$ | 111.9$^b$ | 5.3$^c$ |
| | 2014 | 27.5$^a$ | 2.6$^b$ | 37.0$^c$ | 1.5$^a$ | 13.4$^b$ | 209.4$^c$ | 19.6$^a$ | 69.6$^a$ | 3.9$^b$ |
| | 2014 | 27.3$^a$ | 3.0$^c$ | 33.5$^b$ | 2.8$^b$ | 11.3$^a$ | 85.9$^a$ | 21.6$^{ab}$ | 107.5$^b$ | 2.0$^a$ |
| $F$-value | | 60.6*** | 89.6*** | 23.3*** | 281.2*** | 5.8** | 226.4*** | 13.2*** | 9.2*** | 444.3*** |
| Potassium rate (kg/ha) (K) | 0.0 | 27.6$^{ab}$ | 2.6 | 32.9$^a$ | 2.0$^a$ | 13.3 | 143.7$^a$ | 21.6 | 102.8 | 3.5$^a$ |
| | 49.8 | 29.6$^b$ | 2.4 | 32.7$^a$ | 2.0$^a$ | 12.0 | 144.4$^a$ | 21.2 | 92.7 | 3.6$^b$ |
| | 99.6 | 27.2$^a$ | 2.6 | 33.2$^{ab}$ | 2.0$^a$ | 13.1 | 150.8$^b$ | 21.1 | 88.3 | 3.8$^b$ |
| | 199.2 | 31.5$^c$ | 2.6 | 36.5$^b$ | 2.2$^b$ | 12.7 | 168.4$^c$ | 22.8 | 101.5 | 3.9$^b$ |
| $F$-value | | 23.3*** | 2.1 | 5.9** | 4.8** | 0.9 | 5.8** | 1.4 | 0.6 | 3.3* |
| Magnesium rate (kg/ha) (Mg) | 0.0 | 28.9 | 2.6 | 33.9 | 2.0 | 12.4 | 152.8 | 21.3 | 100.0 | 3.7 |
| | 15 + 3 | 29.0 | 2.5 | 33.7 | 2.1 | 13.1 | 150.9 | 22.0 | 92.7 | 3.7 |
| $F$-value | | 0.1 | 3.0 | 0.0 | 0.6 | 1.5 | 0.2 | 1.4 | 0.7 | 0.1 |
| ***F*-values for interaction** | | | | | | | | | | |
| Y × K | | 13.6*** | 2.3* | 0.4 | 1.2 | 0.6 | 2.0 | 2.7* | 1.7 | 1.6 |
| Y × Mg | | 1.4 | 2.4 | 2.8 | 1.4 | 2.9 | 5.0** | 1.1 | 0.6 | 0.0 |
| K × Mg | | 0.9 | 1.1 | 0.6 | 2.0 | 0.6 | 0.2 | 1.0 | 0.4 | 1.1 |
| Y × K × Mg | | 4.2** | 0.8 | 1.4 | 2.5* | 1.0 | 1.7 | 1.8 | 0.8 | 0.1 |

*$P$ < 0.05; **$P$ < 0.01; ***$P$ < 0.001; the same letter indicates a lack of significant differences within the treatment. $N_{tot}$ – total nitrogen; DM – dry matter

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Table 6. Correlation matrix between nutrients in winter oilseed rape stems at the stage of inflorescence development (BBCH 57–59) and seed yield, $n$ = 24

| | $N_{tot}$ | P | K | Mg | Ca | Fe | Mn | Zn | Cu |
|---|---|---|---|---|---|---|---|---|---|
| Yield | –0.46* | 0.73*** | 0.43* | 0.64** | –0.44* | –0.40 | –0.18 | –0.14 | –0.78*** |
| $N_{tot}$ | 1.0000 | –0.45* | –0.11 | –0.13 | 0.28 | 0.21 | 0.42* | 0.22 | 0.55** |
| P | | 1.00 | 0.45* | 0.57** | –0.37 | –0.43* | –0.44* | –0.13 | –0.87*** |
| K | | | 1.00 | –0.11 | 0.14 | 0.48* | –0.26 | –0.30 | –0.22 |
| Mg | | | | 1.00 | –0.52** | –0.86*** | 0.28 | 0.49* | –0.73*** |
| Ca | | | | | 1.00 | 0.50 | 0.17 | –0.14 | 0.56** |
| Fe | | | | | | 1.00 | –0.14 | –0.42* | 0.64** |
| Mn | | | | | | | 1.00 | 0.67*** | 0.33 |
| Zn | | | | | | | | 1.00 | 0.01 |

*$P$ < 0.05; **$P$ < 0.01; ***$P$ < 0.001; $N_{tot}$ – total nitrogen

ing the same yearly trend. This type of trend indicates a good synchronization between supplies of these three nutrients from soil with the rate of the biomass increase. The increase in the nutrient content during WOSR vegetative growth was recorded only for Cu.

A significant effect of K input on the content of other nutrients was recorded for $N_{tot}$, P, Mg, and Zn. The content $N_{tot}$ and Mg in WOSR leaves increased in accordance to the increasing K rates. The reversed trend was found for P. Contents of all these three nutrients significantly depended on the interaction of K × Mg in consecutive years of study. The significant P content decrease in response to the increasing K rates, indirectly indicates that its supply to WOSR plants just before flowering was a yield limiting factor (Table 4). Magnesium application resulted in a significant increase in the content of K, and Ca, but a simultaneous decrease in the Fe content. The stepwise analysis clearly showed that the yield of WOSR, in spite of P shortage, significantly depended on the interaction of Fe and Cu:

$$Y = 4.02^{**} + 0.022Fe^{***} - 0.3Cu^{**} \text{ for } n = 24, R^2 = 0.71.$$

The obtained equation informs that at the late stage of inflorescence development, Fe was the nutrient, exerting the strongest limiting impact on yield. This equation explains the response of WOSR to the foliar application of Fe (Grzebisz et al. 2010).

The content of nutrients was also analyzed in WOSR stems (Table 5). The yearly trends of $N_{tot}$, P, Ca, and Cu contents followed patterns observed at the rosette stage. Quite opposite trends were recorded for Mg, and Fe. With respect to the trends observed for leaves in BBCH 57–59, the same trends were found for P and Ca. However, P exerted a positive, whereas Ca, a negative impact on the yield (Table 6). A rather opposite trend in the nutrients content with respect to their content in leaves was found for $N_{tot}$, Fe, and Zn, which were negatively correlated with the yield. The Cu content was negatively correlated with P and Mg. The negative relationship with yield clearly indicates that Cu content in the first two years was in excess.

The effect of K treatments on the nutrient content was significant for $N_{tot}$, K, Mg, Fe and Cu. The progressive impact of the increasing K rates was recorded for K, Mg, Fe, and Cu. The stepwise analysis showed that the content of nutrients in WOSR stems can be used for yield prediction:

$$Y = 0.94 + 0.065K^{**} + 0.97Mg^{***} - 0.01Zn^{***} \text{ for } n = 24, \text{ and } R^2 = 0.89.$$

Among the obtained three regression models, the highest predictive value, based on the $R^2$ was found just for stems. This finding clearly explains the view on the stage of inflorescence as the crucial stage for WOSR yield (Weymann et al. 2015). Potassium shortage, which was first revealed at the rosette stage, persisted up to flowering. A shortage of K during this stage can significantly decrease the number of seeds per plant, which is the key yield forming factor (Pan et al. 2017). The limiting effect of Mg on yield corroborates its importance for high-yielding WOSR (Ren et al. 2013, Szczepaniak et al. 2015).

The study clearly showed that insufficient supply of K to WOSR can significantly disturb yield development during vegetative stages of the crop growth. The K deficiency due to its low supply from both soil or fertilizers or negative impact of other factors, like spring frost or drought can

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reveal in stems, but not in leaves. The diagnosis of WOSR nutritional status at later stages of its growth, but limited only to leaves does not deliver a reliable set of data to make a good prediction of the final yield.

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