doi: 10.17221/150/2015-PSE

Nutritional status of winter oilseed rape in cardinal stages of growth as the yield indicator

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ABSTRACT

Nutritional status of the seed crop during its vegetative growth is a tool for a reliable yield prognosis. This approach has been validated for oilseed rape in three 2007/2008, 2008/2009, and 2009/2010 seasons. The field experimental design was: untreated control, NP, NPK, NPKMgS1 (1/3 total MgS rate, spring applied), NPKMgS2 (total rate, autumn), NPKMgS3 (2/3 – autumn, 1/3 – spring). The concentrations of N, P, K, Ca, Mg, Mn, Zn, and Cu were measured in two stages: rosette (whole plant) and flowering (leaves). The yield prognosis was based on path analysis and stepwise regression. The elevated concentration of P, Ca, and Zn in plants at the rosette stage was the early symptom of nutrient imbalance. The Mg concentration in plant leaves at flowering was revealed as the decisive yield predictor. The manner of its management in plant canopy during the yield forming period (YFP) was crucial for the harvested yield. It was documented that each factor leading to increase in Ca but decrease in Mg concentration resulted in yield decrease. The key reason of Mg shortage was its low uptake during the YFP and simultaneous increase in Mn concentration.

Keywords: balanced fertilization; nutrient concentration; plant parts; *Brassica napus*

Oilseed rape has became one of the most important oil crops within the last two decades. The main reason behind this trend is its multifunctional usage, both as food oil and bio-oil (FAOSTAT 2015). The increase of the harvested area within last 20 years was huge, extending from 19.8 million ha in 1993 to 36.4 in 2013. At the same time, yield showed much lower progress, increasing from 1.318–1.994 t/ha. The key reasons for the slower yield increase is the large amount of required nutrients and high sensitivity of plants to damage in winter (Schulte auf'm Erley et al. 2011, Peklová et al. 2012).

Nitrogen is the crucial nutrient for oilseed rape both during vegetative and reproductive stages. The efficiency of biomass production depends on nitrogen supply, which is a decisive factor for both dry matter production and its subsequent partition among plant tissues (Barłóg and Grzebisz 2004). However, nitrogen efficiency depends on other nutrients, which does not refer only to K, P, but also to S, Mg, and micronutrients. Therefore, the intensive production of this crop can be achieved provided a well-balanced supply of nutrients, including magnesium (Grzebisz et al. 2010).

As suggested by Sylvester-Bradley et al. (2002), the whole growth season of a seed crop can be divided into three major periods. The crop foundation period (CFP) extends in oilseed rape from sowing up to the rosette stage. The yield formation period (YFP) covers stages, extending from the rosette up to the onset of flowering. The yield realization period (YRP) based on the canopy production potential established before flowering. The crossing of each consecutive period, known as cardinal stages in yield formation, is the appropriate time-point for nutrient status determination.

The first objective of the conducted study was to assess the impact of balanced supply of nutrients, with special attention to magnesium, on oilseed rape nutritional status in cardinal stages of yield formation. The second objective was to evaluate the yield of seeds based on nutrient concentration in leaves measured at the rosette stage, and the onset of flowering.

doi: 10.17221/150/2015-PSE

MATERIAL AND METHODS

Studies on winter oilseed rape nutritional status in cardinal stages of growth were carried out during three seasons 2007/2008, 2008/2009, and 2009/2010 at Donatowo (52°04'N, 16°51'E), Poland. The field experiment was established on a soil originated from loamy sand underlined by sandy loam, classified as Albic Luvisol. Soil fertility as indicated by agrochemical characteristics was satisfactory for producing high yield of seeds (Table 1). The study was based on the one-factorial trial, consisting of six treatments, replicated four times: untreated control (UC), NP, NPK, NPKMgS1 (1/3 total MgS rate, spring applied), NPKMgS2 (total rate, autumn), NPKMgS3 (2/3 – autumn, 1/3 – spring). Cv. Chagall was sown at the rate of 3.0 kg/ha seeds in the last decade of August. At maturity, plants were harvested from the area of 15 m^2 by a plot combine harvester (Classic Wintersteiger AG, Ried, Austria).

Phosphorus (di-ammonium phosphate, 30.1 kg P/ha) and potassium as muriate of potash and/or Korn-Kali (149.4 kg K/ha) was applied prior to sowing in rates adjusted to the soil test class and treatment. Magnesium and sulphur were applied as Korn-Kali and/or Epsom salt in accordance with the treatment schedule (16.3 kg Mg/ha and 18 kg S/ha). Plants were dressed with nitrogen (ammonium nitrate, 34% N) at the rate of 27 kg N/ha before sowing, 102 kg N/ha before spring's regrowth (21 BBCH) and 78 kg/ha at 30 BBCH.

Plant materials for dry matter (DM) yield and element concentration were sampled from an area of 1.0 m^2 at (i) rosette (30 BBCH); (ii) beginning of flowering (61 BBCH). Sub-samples of leaves were dried (65°C). Nitrogen concentration was determined by a standard macro-Kjeldahl procedure. Plant material for other nutrients was ashed at 600°C, and next dissolved in 33% HNO_3. Phosphorus concentration was determined by the vanadium-molybdenum method; potassium and calcium by the flame-photometry; magnesium, and micronutrients by atomic-absorption spectrometry – flame type. All results are expressed on the dry matter basis.

The obtained data were subjected to the analysis of variance (Statistica 10, StatSoft, Inc., Tulsa, USA). The differences between treatments were evaluated with the Tukey's test. In tables, figures, and equations, results from the *F*-test (***$P \leq 0.1\%$, **$P \leq 1\%$, and *$P \leq 5\%$) are given. The path diagram was constructed to assess the impact of all studied nutrients as independent variables on yield treated as the dependent variable. The choice of the key predictor is based on the highest value of the correlation coefficient for each set of variables. The developed regression models rely on the computing procedure, in which a consecutive variable was removed from the multiple linear regressions in the step-by-step manner (Konys and Wisniewski 1984).

RESULTS AND DISCUSSION

Yield of seeds. Oilseed rape canopy exposed to the impact of external conditions for 330 days resulted, resulting in yield variability (Diepenbrock 2000, Schulte auf'm Erley et al. 2011). The highest yield of seeds, averaged over fertilizing treatments, was harvested in 2008 and the lowest in 2010 (Figure 1). The key reason of yield variability was plant density, which amounted to 35.7 in 2008, 51.2 in 2009 and 21.3 in 2010 plants per m^2. The optimum plant density ranges from 30–40 per m^2 (Spychaj-Fabisiak et al. 2011). The primary reason for low plant density in 2010 was soil crust due to high precipitation during seed germination (111 mm in August and September 2009 vs. 67 mm long-term average (1961–2010). The second disaster was frost in January 2010 (down to –22°C). In 2008, the highest yield was harvested in the MgS2 treatment. In 2010, the same trend of oilseed rape response to MgS fertilizers was observed, but it

Table 1. Agrochemical characteristics of soils under study

Year	pH_{KCl} (1 mol/L)	Content of nutrients (mg/kg soil)						N_{min} (kg/ha)
		P^1	rating	K^1	rating	Mg^2	rating	
2008	6.4	96	very high	151	high	45	medium	66
2009	6.6	89	very high	164	high	52	high	75
2010	6.0	68	high	104	medium	75	very high	68

[1]Egner-Riehm method; [2]Schachtschabel method; N_{min} – mineral nitrogen

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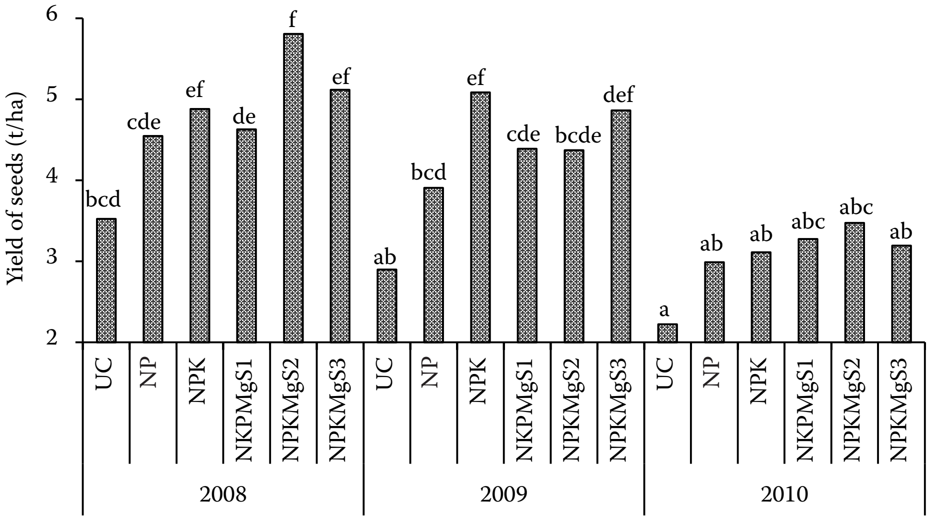

Figure 1. Effect of balanced fertilization of yield on seeds in consecutive years. The same letters mean a lack of significant differences at $P \leq 0.05$. UC –untreated control; NP; NPK; NPKMgS1 – 1/3 total MgS rate, spring applied; NPKMgS2 – total rate, autumn; NPKMgS3 – 2/3 – autumn, 1/3 – spring

was not significant. In 2009, harvested yields were the highest in the NPK plot. This inconsistence in oilseed rape response to the applied nutrients can be explained by magnesium impact on nitrogen use efficiency (Orlovius 2000).

Nutritional status of oilseed rape at the rosette stage. Nutrient concentrations in leaves of oilseed rape at 30 BBCH responded to experimental factors and years (Table 2). The recorded concentrations of nutrients, averaged over treatments, were in optimum ranges except P in 2009, N in 2008, and Zn in 2008, and 2009. According to Merrien (1992) perfect ranges for these three nutrients are as follows: N – 55 g/kg, P – 5.8 g/kg, and Zn – 37.5 mg/kg DM. Nitrogen and K concentration was significantly lower in 2008 compared with other years. Phosphorus concentration showed the highest seasonal variability among the studied nutrients. This phenomenon can be explained, at least partly, by variability in plant density and ample P supply as indicated by the content of soil available phosphorus (Table 1). The same pattern of year-to-year variability was also observed for Ca. Zinc concentration was considerably higher in 2010 as compared with other years. A significant relationships was found between respective pairs of these three elements. In addition, zinc concentration showed an important relationship with Mg and Mn (Table 3).

Nutrient concentration in leaves, except Mn and Cu, depended on applied fertilizers. However, the only N, P and K responded to the interaction

Table 2. Statistical evaluation of nutrient concentration in winter oilseed rape at the rosette stage (mean of three years)

Factor	Factor level	Macronutrients (g/kg DM)					Micronutrients (mg/kg DM)		
		N	P	K	Ca	Mg	Zn	Mn	Cu
Fertilizing treatment (FT)	UC	36.1^{a}	5.9^{ab}	34.6^{a}	11.8^{a}	1.8^{a}	28.0^{a}	37.6	5.3
	NP	50.3^{b}	5.6^{a}	45.0^{b}	14.8^{ab}	2.3^{b}	33.0^{ab}	44.2	6.1
	NPK	52.4^{b}	6.3^{abc}	47.2^{b}	14.9^{ab}	2.5^{b}	36.3^{b}	45.3	6.4
	NPKMgS1	51.1^{b}	6.7^{bc}	48.1^{b}	15.7^{b}	2.4^{b}	34.9^{b}	49.9	6.1
	NPKMgS2	49.9^{b}	6.4^{abc}	47.7^{b}	16.2^{b}	2.4^{b}	33.6^{ab}	44.0	6.1
	NPKMgS3	51.6^{b}	6.9^{c}	49.4^{b}	15.5^{ab}	2.5^{b}	35.8^{b}	43.2	6.1
Year (Y)	2008	44.2^{a}	5.2^{b}	41.7^{a}	13.3^{b}	2.2^{a}	29.5^{a}	38.3^{a}	5.6^{a}
	2009	51.1^{b}	2.2^{a}	46.3^{b}	10.4^{a}	2.2^{a}	29.8^{a}	41.3^{a}	6.3^{b}
	2010	50.4^{b}	11.5^{c}	48.1^{b}	20.8^{c}	2.5^{b}	41.4^{b}	52.5^{b}	6.2^{ab}
F for FT × Y		*	***	*	ns	ns	ns	ns	ns

The same letters mean a lack of significant differences at $P \leq 0.05$. *F*-probability values: *$P \leq 0.05$; ***$P \leq 0.001$; ns – no significantly; DM – dry matter; UC –untreated control; NP; NPK; NPKMgS1 – 1/3 total MgS rate, spring applied; NPKMgS2 – total rate, autumn; NPKMgS3 – 2/3 – autumn, 1/3 – spring

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Table 3. Matrix correlation for concentration of nutrients and yield at the rosette stage (n = 12)

Nutrient	P	K	Ca	Mg	Zn	Mn	Cu	Total seed yield
N	–0.14	0.60*	–0.10	0.47	0.25	0.33	0.81**	–0.37
P	1.00	0.05	0.98***	0.78**	0.84**	0.65	–0.33	–0.75**
K		1.00	0.14	0.44	0.13	0.25	0.68*	–0.29
Ca			1.00	0.80**	0.83**	0.68*	–0.26	–0.80**
Mg				1.00	0.90***	0.71*	0.27	–0.88***
Zn					1.00	0.75**	0.06	–0.89***
Mn						1.00	0.15	–0.82**
Cu							1.00	–0.12

*$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$

of year and fertilizing treatments. The lowest N concentration was an attribute of plants grown in the UC plot. Its level increased in the order: 2008 (29) < 2009 (38) < 2010 (41 g N/kg DM). In treatments with N, it ranged from 47–56 g N/kg DM. Phosphorus concentration showed high seasonal variability. In 2008, it reached the highest value in the NPK, but in 2009 in the NP treatment. In 2010, it reached the maximum value in the UC plot. This trend underlines high capacity of the soil to supply P in 2010. The maximum concentration of Ca was noted in plants fertilized with Mg in autumn in the full rate. Concentration of Zn reached the uppermost value in plants fertilized with NPK.

The impact of plant nutritional status on seed yield was evaluated based on two sets of data. The first, representing all treatments was termed, imbalanced fertilizing system (IBFS). The second one, consisting of NPK and NPKMgS treatments, was termed balanced fertilizing system (BFS). The stepwise regression model indicated on K, Ca, and Cu as the best set of variables in the IBFS for prediction of the total seed yield (TSY):

$$TSY = 663.2^{**} + 183.5K^{**} - 161.5Ca^{**} - 142.2Cu^{*}$$
for n = 18 and R^2 = 0.46.

The best set of variables in the BFS was determined in two-step procedure. The highest correlation coefficient for nutrients was found for zinc ($r = -0.89^{***}$) (Table 3). Its direct effect, as shown in Figure 2a, was much lower compared to those exerted by P and Ca. Their indirect effects on the value of the coefficient of correlation for Zn were huge, but contradict. The effect of this set of variables on yield was corroborated by the stepwise regression models:

$$TSY = 1114^{***} + 389.8P^{*} - 312Ca^{*} - 12.8Zn^{**}$$
for n = 12 and R^2 = 0.77;

$TSY = 902.3^{***} - 13.3Zn^{***}$ for n = 12 and R^2 = 0.77.

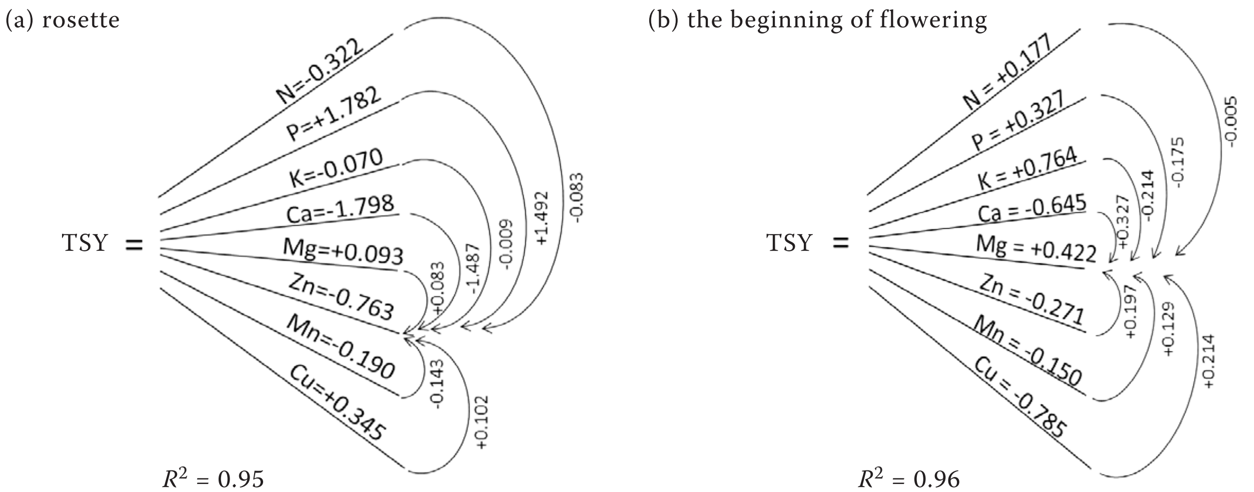

Figure 2. The path-diagram of oil-seed rape nutritional status in leaves and yield of seeds. TSY – total seed yield

doi: 10.17221/150/2015-PSE

The observed imbalance was due to an elevated concentration of P and Ca in plants. The upraised concentration of Zn, as noted in 2010, can be considered as the early signal of plant nutritional disorder. According to Diatta (2013) oilseed rape in the rosette stage is highly sensitive to soil Zn supply. This author stated that the optimum Zn concentration in plants, ranging from 15.3–39.7 mg/kg DM, is sufficient to cover oilseed rape requirement.

Nutritional status of oilseed rape at the beginning of flowering. The optimum ranges of the key nutrient in oilseed rape leaves at the onset of flowering were 5–6 g/kg for P, 27–43 g/kg for K, and 28–52 mg/kg DM for Zn (Barłóg et al. 2005). The recorded concentrations of nutrients, averaged over treatments, were in optimum ranges except P in 2008 and 2010, K in 2008, and Ca in 2009 (Table 4). The strongest year-to-year variability showed P, Ca, and Cu. The first two nutrients followed the pattern observed in the rosette stage. The quite opposite trend was recorded for K. Its concentration responded to the interaction of fertilizing treatments and years. Magnesium concentration showed high variability due to significant interaction of years and fertilizing treatments. It was negatively correlated with Zn and Mn (Table 5). For Mn, this trend is explained by its double increase during the period of stem extension, which resulted in simultaneous Mg_c decrease:

$$\text{IBFS: } Mg_c = 0.194 - 0.0033Mn_{YFP} \text{ for } n = 18, R^2 = 0.47 \text{ and } P \leq 0.01;$$

$$\text{BFS: } Mg_c = 0.22 - 0.0038Mn_{YFP} \text{ for } n = 12, R^2 = 0.59 \text{ and } P \leq 0.01.$$

The variability of the seed yield was significantly related to changes in nutrient concentration in leaves at flowering. The highest, and positive value of the correlation coefficient was found for Mg ($r = +0.90$) (Table 5). The direct effect of Mn on seed yield was much smaller compared to straight effects exerted by K, Ca and Cu (Figure 2b). The correlation coefficient for Mg was negatively affected by Ca, by K, and Cu. The regression models fully underline the decisive effect of Mg and Ca concentration balance on seed yield prediction:

$$\text{IBFS: TSY} = 168.2^{*} + 308.9P^{*} - 106.5Ca^{**} + 1408Mg^{***} \text{ for } n = 18 \text{ and } R^2 = 0.85;$$

$$\text{BFS: TSY} = 117.8 - 30.7Ca^{**} + 1309Mg^{***} \text{ for } n = 12, R^2 = 0.90.$$

These four equations implicitly indicate on Mg as the important nutrient for oilseed rape. Its shortage at the onset of flowering resulted in yield decrease. As reported by Weymann et al. (2015) the period of oilseed rape, extending from 50–65 BBCH, is crucial for the onset of pods and seeds. Based on the own study, it can be concluded that the degree in Mg concentration change (ΔMg_c) during the stem extension (YFP) is a very important characteristic of oilseed rape nutritional status. It was documented that ΔMg_c during the YFP was significantly higher in the BFS. Therefore, magnesium concentration during the YFP should be considered as an important factor of the yield

Table 4. Statistical evaluation of nutrient concentration in leaves of winter oilseed rape at flowering (mean of three years)

Factor	Factor level	Macronutrients (g/kg DM)					Micronutrients (mg/kg DM)		
		N	P	K	Ca	Mg	Zn	Mn	Cu
Fertilizing treatment (FT)	UC	31.3^{a}	4.5	26.8^{a}	35.8	2.8^{a}	32.6^{a}	62.1	4.9
	NP	44.3^{b}	5.1	32.5^{bc}	31.5	3.0^{ab}	45.8^{b}	75.1	6.0
	NPK	40.0^{b}	5.5	34.3^{bcd}	34.2	3.3^{bc}	44.1^{b}	79.9	6.1
	NPKMgS1	42.7^{b}	5.1	36.6^{cd}	33.6	3.2^{bc}	50.2^{b}	91.1	6.4
	NPKMgS2	42.2^{b}	5.4	31.5^{b}	33.3	3.1^{bc}	44.2^{b}	83.5	5.8
	NPKMgS3	42.0^{b}	5.0	37.1^{d}	35.4	3.3^{c}	48.2^{b}	77.4	6.4
Year (Y)	2008	36.8^{a}	4.4^{b}	24.0^{a}	31.7^{b}	3.7^{c}	36.9^{a}	61.2^{a}	4.2^{a}
	2009	47.7^{b}	2.2^{a}	43.2^{c}	21.6^{a}	2.9^{b}	46.9^{b}	80.0^{ab}	8.0^{c}
	2010	36.7^{a}	8.7^{c}	32.1^{b}	48.6^{c}	2.7^{a}	48.7^{b}	93.3^{b}	5.7^{b}
F for FT × Y		ns	ns	***	ns	***	*	ns	ns

The same letters means a lack of significant differences at $P \leq 0.05$. *F*-probability values: $^{*}P \leq 0.05$; $^{***}P \leq 0.001$; ns – no significantly; DM – dry matter; UC –untreated control; NP; NPK; NPKMgS1 – 1/3 total MgS rate, spring applied; NPKMgS2 – total rate, autumn; NPKMgS3 – 2/3 – autumn, 1/3 – spring

doi: 10.17221/150/2015-PSE

Table 5. Matrix correlation for concentration of nutrients and yield at flowering (n = 12)

Nutrient	P	K	Ca	Mg	Zn	Mn	Cu	Total seed yield
N	–0.78**	–0.70*	–0.81**	–0.00	0.37	–0.07	0.75**	0.28
P	1.00	–0.41	0.98***	–0.55	0.17	0.58*	–0.44	–0.77**
K		1.00	–0.38	–0.25	0.55	0.40	0.99	–0.10
Ca			1.00	–0.52	0.16	0.55	–0.43	–0.76**
Mg				1.00	–0.70*	–0.85**	–0.23	0.90***
Zn					1.00	0.63*	0.53	–0.65*
Mn						1.00	0.38	–0.86***
Cu							1.00	–0.08

*$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$

of seeds. This conclusion was fully corroborated by the double increase in the R^2 value in the BFS:

$$\text{IBFS: TSY} = 317.1 + 1055.3\Delta Mg_c \text{ for } n = 18, R^2 = 0.43 \text{ and } P \leq 0.01.$$

$$\text{BFS: TSY} = 334.9 + 1289.7\Delta Mg_c \text{ for } n = 12, R^2 = 0.87 \text{ and } P \leq 0.001.$$

The regression model developed for the BFS set of treatments underlines the importance of nutritional balance between Ca and Mg concentration in leaves at the onset of oilseed rape flowering. Magnesium acts as the nutrient balancing excess of calcium. The elevated concentration of calcium can be explained by its high uptake by oilseed rape plants, especially under conditions of reduced plant density and/or water shortage. In the studied case, Mg concentration was negatively impacted by Mn; as reported in this study, any increase in its concentration during the stem extension phase, led to Mg concentration decrease.

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Received on March 4, 2015
Accepted on June 1, 2015

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