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ORIGINAL PAPER

EFFECT OF MICRO-GRANULAR STARTER FERTILIZER ON THE MICRONUTRIENT CONTENT OF WINTER RAPESEED BIOMASS*

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Abstract

The effectiveness of mineral fertilization can be improved through starter or band application. This technique reduces fertilizer doses (costs) and minimizes environmental risks. This paper presents the results of a 3-year study investigating the effects of a micro-granular starter fertilizer (MSF) applied in the seed zone on the micronutrient content and micronutrient uptake by the biomass of winter oilseed rape (*Brassica napus* L.) during the autumnal growth and after harvest. The study was carried out at the Agricultural Experiment Station in Bałcyny (NE Poland) in 2012-2015. During the autumnal growth, micronutrient concentrations (in particular Mn and Fe) were higher in the roots than in the leaf rosettes of winter oilseed rape. The application of the MSF in autumn increased the content of Cu, Zn and Fe but decreased Mn levels in rosettes. The application of the MSF during sowing increased the concentrations of Zn, Mn and Fe in roots. During the autumnal growth, the micronutrient uptake was estimated at 481.0 g Fe ha^{-1}, 81.8 g Mn ha^{-1}, 56.5 g Zn ha^{-1} and 7.7 g ha^{-1} Cu. The MSF improved the micronutrient uptake by winter oilseed rape in autumn. In post-harvest biomass, the highest Fe and Mn content was determined in roots, and the highest Cu and Zn concentrations were detected in seeds. The MSF increased the micronutrient content of seeds (Cu, Mn and Fe) and straw (Cu, Zn, Mn and Fe). In treatments where the NPK fertilizer was applied before sowing (at the standard or half the standard dose), the application of the MSF during sowing decreased Cu and Mn concentrations and increased the Zn and Fe content of post-harvest residues (roots). Micronutrient (Cu, Zn, Mn, Fe) uptake by seeds and straw was significantly higher under the influence of the MSF. The application of the MSF in autumn decreased the micronutrient uptake by the winter oilseed rape roots.

Keywords: *Brassica napus*, nutrients, uptake.

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INTRODUCTION

In Europe, the average yield of winter oilseed rape reaches 3-4 Mg ha^{-1}. Under favourable weather conditions, seed yields of 5 or even 6 Mg ha^{-1} are not uncommon in large-area farms that specialize in crop production (Rathke et al. 2006, Oleksy et al. 2018). From the physiological and morphological point of view, the yield potential of winter oilseed rape is achieved during the autumn growth. Plant density at harvest, the potential number of side branches and, indirectly, the number of siliques are highly influenced by weather conditions in autumn (Jankowski 2007, Oleksy et al. 2018).

Winter oilseed rape plants that develop at least 6-9 rosette leaves with the maximum height of the shoot apical meristem of 2-3 cm are characterized by the highest frost resistance. In autumn, roots should penetrate the entire arable layer of soil, and the root neck diameter should be at least 5-8 mm (Muśnicki 1989). Plants with the above growth habit are not only most resistant to frost and variable temperatures, but they are also characterized by high vigour in spring, they compete effectively against weeds and form a large number of flower buds and siliques, which are indicative of high yield potential.

The autumn growth of leaf rosettes in winter oilseed rape is influenced by the combined effects of all production factors, but in addition to the seeding date and method, fertilization plays a key role in the development of rosettes (Budzyński 1986). The effectiveness of fertilization is determined by the availability of soil macronutrients and micronutrients. However, drought or sub-optimal soil pH can decrease the availability of soil nutrients even in the most fertile soils (Grzebisz, Musolf 1999, Pająk, Durak 2018). Granular fertilizers minimize nutrient loss and increase the availability of macronutrients and micronutrients in soil. Granular fertilizers are less susceptible to leaching into deeper soil layers, and dissolving granules are gradually absorbed by plants (Obraniak, Gluba 2009).

Fertilizer broadcasting on the surface of soil is the most popular method of fertilizer application in agricultural practice. However, the uppermost soil layer dries up during drought and decreases the availability of nutrients for crops. Localized fertilization, where the fertilizer is placed in the seed zone, promotes nutrient uptake by crops (Valluru et al. 2010, Nkebiwe et al. 2016). This fertilization method is widely applied in the USA (Hergert et al. 2006). In Europe, it is generally referred to as starter or band application of fertilizers (Günter 2002).

In comparison with fertilizers that are broadcast over the soil surface, starter fertilizers increase nutrient uptake and nutrient concentrations in biomass, improve initial vigour, increase growth rates, contribute to stand uniformity and increase biomass yield (Su et al. 2015, Abit et al. 2016).

The objective of this study was to determine the effect of a micro-granulated starter fertilizer (MSF) placed with the seeds of winter oilseed rape on the content and uptake of micronutrients in rosette leaves and roots harvested in autumn, and in whole plants at the fully ripe stage.

MATERIALS AND METHODS

Experimental site

The experiment was conducted in 2012-2015, at the Agricultural Experiment Station in Bałcyny (53°35′46.4″ N, 19°51′19.5″ E, elevation of 137 m) in NE Poland. The station is owned by the University of Warmia and Mazury in Olsztyn. The experiment involved the following autumn fertilization treatments: (i) 30 kg N ha^{-1}, 35 kg P ha^{-1}, 100 kg K ha^{-1} (NPK); (ii) 30 kg N ha^{-1}, 35 kg P ha^{-1}, 100 kg K ha^{-1} + 25 kg ha^{-1} micro-granulated starter fertilizer (NPK+MSF); (iii) 15 kg N ha^{-1}, 17.5 kg P ha^{-1}, 50 kg K ha^{-1} + 25 kg ha^{-1} MSF (½ NPK + MSF), (iv) only 25 kg ha^{-1} MSF. NPK fertilizers were applied 3-4 days before sowing and were mechanically incorporated into the soil to a depth of 5-8 cm. Nitrogen was applied in the form of ammonium nitrate (34% N), P was applied as enriched superphosphate (17% P), and K – as potash salt (60% K). The Physiostart® micro-granulated starter fertilizer with a granule diameter of 0.6-0.8 mm contained 8% N ($N\text{-}NO_3$ only), 12% P, 10% Ca, 9% S and 2% Zn. It was distributed with the use of a precision seeder equipped with a fertilizer applicator. The fertilizer was placed in the immediate vicinity of sown seeds.

In spring, all treatments were fertilized with 220 kg N ha^{-1} in two applications: 120 kg N ha^{-1} in the form of ammonium nitrate (34% N) and ammonium sulfate (21% N and 24% S) at the beginning of the growing season, and 100 kg N ha^{-1} in the form of ammonium nitrate (34% N) at the beginning of bud formation. 45 kg S ha^{-1} was applied with the first dose of N (ammonium sulfate, 21% N and 24% S).

Experimental design and crop management

The experiment followed a randomized complete block design with three replications. The plot size was 25.2 m^2 (7.2 m × 3.5 m). Each year, the experiment was established on Haplic Luvisol soil originating from boulder clay (IUSS 2006). The content of C_{org}, plant-available P, K, Mg, , Cu, Zn, Mn, Fe, pH in 1 mol dm^{-3} KCl was determined in the 0-30 cm soil horizon before the experiment. Soil samples were collected from three horizons (0-30, 30-60 and 60-90 cm) before the experiment to determine the content of mineral nitrogen ($N\text{-}NH_4$ and $N\text{-}NO_3$) – Table 1. The content of $N\text{-}NH_4$ in the soil was determined colorimetrically with Nessler’s reagent, and $N\text{-}NO_3$ levels were determined colorimetrically with phenoldisulfonic acid (Shimadzu UV-1201V spectrophotometer). Soil organic C was determined using the Kurmies’ modified method (Shimadzu UV-1201V spectrophotometer, Shimadzu Corporation

Table 1

Chemical properties of the analyzed soil

Years	pH (1 mol dm^{-3} KCl)	C_{org} (%)	N-NO_3 (mg kg^{-1})			N-NH_4 (mg kg^{-1})			Available macronutrients and micronutrients (mg kg^{-1})							
			I†	II	III	I	II	III	P	K	Mg	SO_4^{2-}	Cu	Zn	Mn	Fe
2012/ /2013	5.52	0.89	9.88	4.77	1.98	2.67	1.73	1.53	60.1	110.1	71	8.3	2.8	18.6	191	2380
2013/ /2014	6.08	1.08	9.71	7.41	5.40	1.57	1.02	1.50	77.2	212.4	62	7.5	2.0	17.9	189	2200
2014/ /2015	6.36	0.89	4.19	0.29	3.35	5.05	0.75	1.52	71.5	98.9	90	11.1	3.8	21.6	198	2450

† soil horizon: I – 0-30 cm; II – 31-60 cm; III – 61-90 cm

Kyoto, Japan). Soil pH was measured using a digital pH meter with temperature compensation (20°C) in deionized water and 1 mol dm^{-3} KCl at a 5:1 ratio. Plant-available P and K were measured by the Egner-Riehm method (using 3.5 mol ammonium lactate acetic acid buffered to pH = 3.75 as extracting solution). Phosphorus was determined by the vanadium molybdate yellow colorimetric method (Shimadzu UV-1201V spectrophotometer, Shimadzu Corporation Kyoto, Japan), and K was determined by atomic emission spectrometry, AES (BWB Technologies UK Ltd. Flame Photometers). Magnesium was extracted with 0.01 M $CaCl_2$ and determined by atomic absorption spectrophotometry, AAS (AAS1N, Carl Zeiss Jena, Germany). Micronutrients (Cu, Zn and Mn) were extracted with 1 M HCl and determined by AAS (AA-6800, Shimadzu Corporation Kyoto, Japan) after extraction in 1 mol dm^{-3} HCl. The content of was determined by nephelometry after extraction in acetate buffer (Shimadzu UV-1201V spectrophotometer, Shimadzu Corporation Kyoto, Japan).

In each year of the study, the previous crop was winter triticale (×*Triticosecale* Wittm. ex A. Camus.). Winter rapeseed hybrid cv. SY Kolumb (canola type) was sown between 17 and 20 August at 33 pure live seeds m^{-2} and inter-row spacing of 45 cm. A growth regulator (37.5 g ha^{-1} paclobutrazol and 75 g ha^{-1} difenoconazole) were applied at the 4-6 leaf stage. Weeds were controlled with 832.5 g ha^{-1} metazachlor and 207.5 g ha^{-1} quinmerac after sowing. The following insecticides were applied four times in spring: the organophosphate insecticide chlorpyrifos at 288 g ha^{-1}, the neonicotinoid insecticide acetamiprid at 24 g ha^{-1}, and two pyrethroid insecticides – deltamethrin at 5 g ha^{-1}, and alpha-cypermethrin at 12 g ha^{-1}. Pathogens were controlled with dimoxystrobin at 100 g ha^{-1} and boscalid at 100 g ha^{-1} at the flowering declining stage (BBCH 65). Winter oilseed rape was harvested at physiological maturity (BBCH 89) with a small-plot harvester (mid-July).

Plant analysis

Leaf rosettes were sampled before the end of the growing season (75 days after sowing (DAS) during the seedling stage in 2012/2013, 81 DAS in 2012/2013, and 90 DAS in 2014/2015) in a random sample of 20 plants from each treatment. The sampled plants (aerial rosette parts and roots) were dried at a temp. of 70°C for 72 h (Binder drying oven, Germany) to determine their dry matter content. Immediately before threshing (332 DAS in 2012/2013, 318 DAS in 2013/2014, and 322 DAS in 2014/2015), 20 mature plants were randomly sampled from every treatment. Root weight was determined immediately after harvest at three random points in each plot. Soil was sampled into a steel cylinder measuring 22.57 cm in diameter and 30 cm in length. Soil and root samples were rinsed with water in a 1 mm mesh sieve. The dry matter content of roots was determined by drying at a temperature of 70°C for 72 h (Binder drying oven, Germany).

Chemical composition of plants

The micronutrient content of plants was determined on a dry weight basis. Dried plants were ground in a laboratory mill (GM 300, Retsch, Germany). The content of Cu, Zn, Mn and Fe was determined by Flame-AAS (Shimadzu UV-1201V spectrophotometer, Shimadzu Corporation Kyoto, Japan). The nutrient uptake was calculated from plant biomass (DM) and nutrient content.

Statistical analysis

Data were analyzed by ANOVA, and treatment means were compared with the Duncan's test at a probability level of 0.05 using Statistica 13 PL (TIBCO Software Inc. 2017). Years and autumn fertilization were the fixed effects, and replication was the random effect.

RESULTS AND DISCUSSION

Micronutrient uptake by winter oilseed rape in autumn

The average weight of a *B. napus* seed ranges from 3 mg to 6 mg, which potentially limits the seed's nutrient reserves. Minerals such as K, P, S, Mg, Fe, Mn and Zn are accumulated mainly in unfolded cotyledons, and the seed coat is abundant in Ca, Cu, Mo and B (Eggert, von Wirén 2013). Minerals are rapidly transported from cotyledons to roots to initiate root development, whereas nutrients accumulated in the seed coat are released and probably again taken up by growing roots (Zhao et al. 2012). Localized fertilizer placement increases nutrient concentrations, stimulates plant growth, leads to changes in root morphology and structure, and improves the uptake of water and dissolved minerals by roots (Nosalewicz 2013). According to Weichmann (1998), the micronutrient content of rosettes in stage BBCH 30 should approximate: Mn – 30-140 mg kg^{-1}, Cu – 4.0-6.2 mg kg^{-1}, Zn – 30-38 mg kg^{-1}, Fe – 60-80 mg kg^{-1}. In the Polish region of Wielkopolska, the application of the NPK fertilizer before sowing increased the micronutrient content of leaf rosettes in stage BBCH 30 by: 8.3 mg Zn kg^{-1}, 7.7 mg Mn kg^{-1} and 1.1 mg Cu kg^{-1} (Szczepaniak et al. 2015).

In the present study, the Cu content of rosette leaves was the highest (5.3 mg kg^{-1} DM) in the NPK+MSF treatment, whereas the remaining fertilization methods (NPK, ½ NPK + MSF, MSF) decreased the Cu content of rosette leaves by 0.8-0.9 mg kg^{-1} DM. The Zn content of rosette leaves was significantly the highest (38.7-39.7 mg kg^{-1} DM) after the application of MSF, regardless of the NPK dose. In MSF treatments, the Mn content of rosette leaves was lowered by 4.0-7.3 mg kg^{-1} DM, and it decreased with a drop in the NPK dose. The Fe content of rosette leaves increased by 21.6-83.1 mg kg^{-1} DM in response to MSF, and the observed that the increase was proportional to a decrease in the NPK dose (Table 2).

In autumn, the Zn (39.3 mg kg^{-1}) and Mn (72.4 mg kg^{-1}) content of roots was the highest in the NPK+MSF treatment. Roots accumulated the highest amounts of Fe (518-520 mg kg^{-1} DM) in response to MSF, irrespective of the NPK dose (Table 2).

In our study, the nutrient uptake in autumn was estimated at 6.6 g Cu ha^{-1}, 51.3 g Zn ha^{-1}, 73.0 g Mn ha^{-1} and 464.0 g Fe ha^{-1}. Approximately 68-79% of these micronutrients were accumulated in the aerial part of rapeseed rosettes (Figure 1).

Table 2

The influence of autumn fertilization on the micronutrient (mg kg^{-1} DM) content of winter oilseed rape plants in autumn across years

Nutrient	Fertilization†			
	NPK	NPK + MSF	½ NPK + MSF	MSF
Leaf rosette				
Cu	4.5^{b}	5.3^{a}	4.4^{b}	4.5^{b}
Zn	35.7^{b}	38.7^{a}	39.7^{a}	39.6^{a}
Mn	55.6^{a}	51.6^{b}	49.6^{bc}	48.3^{c}
Fe	263.1^{d}	284.7^{c}	315.9^{b}	346.2^{a}
Roots				
Cu	4.6	4.7	4.9	4.9
Zn	33.2^{b}	39.3^{a}	33.2^{b}	28.8^{c}
Mn	53.6^{c}	72.4^{a}	60.5^{b}	53.7^{c}
Fe	389.6^{b}	519.7^{a}	519.5^{a}	517.8^{a}

† NPK: 30 kg N ha^{-1}, 35 kg P ha^{-1}, 100 kg K ha^{-1}; NPK + MSF: 30 kg N ha^{-1}, 35 kg P ha^{-1}, 100 kg K ha^{-1} + 25 kg ha^{-1} MSF; ½ NPK + MSF: 15 kg N ha^{-1}, 17.5 kg P ha^{-1}, 50 kg K ha^{-1} + + 25 kg ha^{-1} MSF; MSF: 25 kg ha^{-1} MSF;
Means with the same letters do not differ significantly at $P \leq 0.05$ in the Duncan's test;
MSF – micro-granulated starter fertilizer.

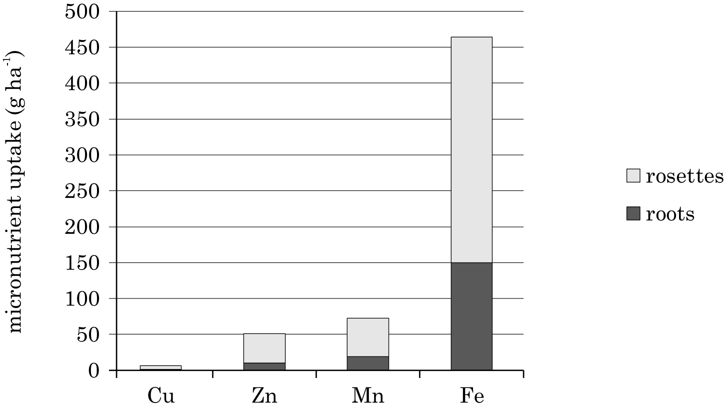

Fig. 1. Nutrient uptake by winter oilseed rape plants in autumn across years (average values for different autumn fertilization methods)

In the Polish region of Wielkopolska, the NPK fertilizer applied to the soil surface increased the content of Mn by 3.4 mg kg^{-1}, Zn – by 3.9 mg kg^{-1}, Cu by 2.0 mg kg^{-1}, and decreased the content of Fe by 78 mg kg^{-1} in rosettes (BBCH 30) relative to the control (unfertilized) treatment (Gaj 2011).

In the current study, iron (365-521 g ha^{-1}) was the most highly accumulated micronutrient in autumn in each year of the study. The autumn uptake of Mn, Zn and Cu was 6-fold, 9-fold and 71-fold lower, respectively, in comparison with Fe uptake (Table 3). In all analyzed seasons, MSF had a positive influence on the micronutrient uptake by winter oilseed rape plants during the autumn growth period. The nutrient uptake was particularly high in treatments where MSF was combined with the NPK fertilizer applied pre-sowing (NPK+MSF). The micronutrient uptake in autumn was determined at 481.0 g Fe ha^{-1}, 81.8 g Mn ha^{-1}, 56.5 g Zn ha^{-1} and 7.7 g ha^{-1} Cu (Table 3).

Table 3

The influence of autumn fertilization on the micronutrient (g ha^{-1}) uptake by winter oilseed rape plants (rosettes + roots) in autumn across years

Nutrient	Fertilization			
	NPK	NPK + MSF	½ NPK + MSF	MSF
Cu	5.7^{b}	7.7^{a}	6.4^{b}	6.4^{b}
Zn	44.0^{b}	56.5^{a}	53.9^{a}	51.5^{ab}
Mn	68.9	81.8	73.6	68.6
Fe	364.6^{b}	481.0^{a}	498.7^{a}	520.9^{a}
∑	483.2^{b}	627.0^{a}	632.5^{a}	647.4^{a}

explanations as in Table 2

Micronutrient content of harvested biomass

In spring, the biomass of healthy winter oilseed rape plants should reach 1.5-2.5 Mg ha^{-1} DM. Between the initiation of plant growth in spring and maturation, plant biomass increases to 14-18 Mg ha^{-1} DM (Jankowski 2007). The uptake and accumulation of micronutrients in different plant organs (roots, shoots, seeds) is determined by the humus content of soil, microbial activity in the rhizosphere, soil pH, soil moisture (Hänsch, Mendel 2009) and fertilization (Jankowski et al. 2014).

In winter oilseed rape, the highest Cu and Zn levels are noted in seeds, moderate Cu and Zn concentrations are noted in root residues, whereas straw is least abundant in the above micronutrients. In the post-harvest residues, roots are characterized by the highest Mn content (46.4 mg kg^{-1} DM). In oil cake and straw, Mn levels were lower by 8.6 and 36.2 mg kg^{-1} DM, respectively (Jankowski et al. 2014). Seeds accumulated 8.6-9.4 mg kg^{-1} DM of B and 69.3-74.9 mg kg^{-1} DM of Fe (Jankowski et al. 2016). In rapeseed straw, Fe concentration was 1.7-fold lower and B content was 1.6-fold higher than in seeds (Bowszys 2001).

In the present study, iron was the most highly accumulated micronutrient in seeds (92 mg kg^{-1} DM on average). The Zn and Mn content of seeds was 2-fold and 3-fold lower, respectively, compared with Fe. Copper was the least accumulated nutrient in seeds (3.5 g kg^{-1} DM). Seeds were most abundant in Cu and Zn. The highest content Fe was noted in roots. Roots contained 4 times more Mn and 4 times more Fe than seeds (Table 4).

The application of the NPK fertilizer increased the micronutrient content of seeds (Szczepaniak et al. 2017). In a study by Szczepaniak et al. (2017), the application of 27 kg N ha^{-1}, 30 kg P ha^{-1} and 149 kg K ha^{-1} before sowing increased the concentration of Zn by 3.0 mg kg^{-1}, Mn – by 4.7 mg kg^{-1} and Cu – by 0.19 mg kg^{-1} relative to the unfertilized treatment.

In our study, the micronutrient (Cu, Mn and Fe) content of seeds was the highest in treatments were MSF was combined with half the standard NPK dose. The application of MSF increased the micronutrient content in straw, but the magnitude of that effect was determined by the NPK dose applied pre-sowing. The application of NPK decreased the content of Cu and Zn (NPK+MSF and ½NPK+MSF) and increased the content of Fe (NPK+MSF) in straw. In roots, the content of Cu, Zn and Fe was higher, whereas the content of Mn was lower in response to MSF (regardless of the NPK dose) – Table 4.

In a study by Spiak et al. (2007), the accumulation of Cu, Zn and Mn was higher in seeds (76%) than in straw (24%). Copper was accumulated mainly in the straw (62%), whereas seeds were most abundant in Zn (81%) and Mn (76%).

In our study, micronutrients were accumulated mainly in straw (44%) and roots (37%), and to a much lesser extent in seeds (19%) – Table 5. Copper and Zn were accumulated mostly in seeds (44-67%) and in straw (22-43%). Manganese was accumulated mostly in straw (52%) and seeds (29%), and Fe – in straw (45%) and roots (42%) – Figure 2.

Table 4

The influence of autumn fertilization on the micronutrient (mg kg^{-1} DM) content of the harvested biomass of winter oilseed rape (BBCH 89) across years

Nutrient	Fertilization			
	NPK	NPK + MSF	½ NPK + MSF	MSF
Seeds				
Cu	3.2^{d}	3.6^{b}	3.7^{a}	3.4^{c}
Zn	41.7	42.6	40.1	41.7
Mn	27.8^{b}	27.1^{b}	30.5^{a}	26.9^{b}
Fe	87.6^{c}	93.1^{b}	103.5^{a}	83.9^{c}
Straw				
Cu	2.5^{b}	2.6^{b}	1.9^{c}	2.7^{a}
Zn	9.2^{b}	9.4^{b}	9.4^{b}	10.6^{a}
Mn	26.9	57.9	28.2	23.5
Fe	205.6^{c}	294.0^{a}	272.4^{b}	97.5^{d}
Roots				
Cu	3.0^{a}	3.0^{a}	2.9^{a}	2.6^{b}
Zn	16.3^{c}	21.3^{a}	21.3^{a}	17.4^{b}
Mn	52.7^{a}	48.3^{b}	50.5^{ab}	47.5^{b}
Fe	765.6^{c}	806.9^{b}	903.5^{a}	658.3^{d}

explanations as in Table 2

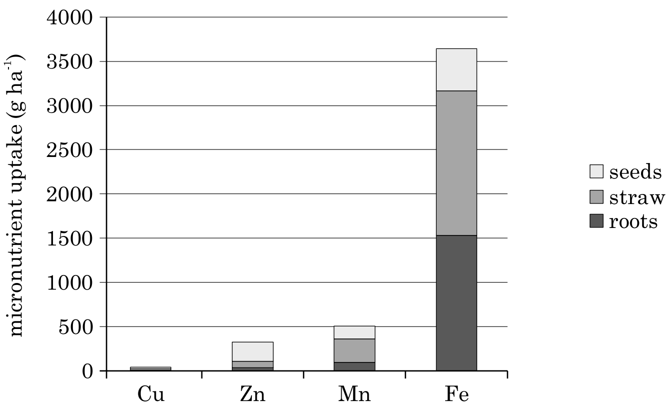

Fig. 2. Nutrient uptake by winter oilseed rape plants in harvested biomass across years (average values for different autumn fertilization methods)

Szczepaniak et al. (2017) demonstrated that the application of NPK fertilizer before sowing increased the micronutrient uptake by winter oilseed rape plants by 80.3 g Zn ha^{-1}, 73.7 g Mn ha^{-1} and 6.3 g Cu ha^{-1} relative to unfertilized plants.

The micronutrient content (Cu, Zn, Mn, Fe) of seeds was significantly higher in response to MSF application, irrespective of the NPK dose. The application of MSF without NPK increased the accumulation of N, Mg, Ca and Zn in straw. The content of the remaining nutrients was significantly higher in MSF treatments with a standard dose of NPK (Cu, Mn, Fe). The uptake of the remaining micronutrients by roots was highest in treatments with standard NPK fertilization without MSF. The application of MSF decreased micronutrient uptake by 17-22% (Table 5).

The overall micronutrient uptake by winter oilseed rape plants was higher in MSF treatments, in particular when the full dose of NPK fertilizer was applied pre-sowing (Table 5). In our study, MSF exerted varied effects of the nutrient uptake by the roots, straw and seeds of winter oilseed rape. Regardless of the NPK dose, MSF significantly increased the levels of Cu, Zn, Mn and Fe in seeds. The application of MSF stimulated the accumulation of micronutrients in straw, and the magnitude of that effect was determined by the dose of NPK applied pre-sowing. In roots, the accumulation of most nutrients was reduced in MSF treatments (Table 5).

Table 5

The influence of autumn fertilization on micronutrient (g ha^{-1} DM) uptake by winter oilseed rape plants (89 BBCH) across years

Nutrient	Fertilization			
	NPK	NPK + MSF	½ NPK + MSF	MSF
Seeds				
Cu	16.3^{c}	19.3^{a}	19.6^{a}	18.3^{b}
Zn	210.4^{c}	231.1^{a}	210.7^{c}	219.3^{ab}
Mn	140.0^{b}	147.3^{b}	160.4^{a}	142.3^{b}
Fe	439.2^{c}	503.8^{b}	541.2^{a}	443.7^{c}
∑	806.0^{b}	901.4^{a}	932.0^{a}	823.5^{b}
Straw				
Cu	16.9^{c}	20.9^{a}	14.6^{d}	19.7^{b}
Zn	62.2^{c}	75.0^{ab}	70.6^{b}	77.6^{a}
Mn	182.8^{b}	482.8^{a}	212.4^{b}	173.1^{b}
Fe	1391.7^{c}	2353.1^{a}	2056.9^{b}	722.6^{d}
∑	1653.7^{c}	2931.8^{a}	2354.6^{b}	993.0^{d}
Roots				
Cu	7.2^{a}	5.5^{b}	5.1^{c}	5.0^{c}
Zn	39.1^{a}	38.1^{a}	37.1^{a}	33.6^{b}
Mn	126.8^{a}	87.3^{b}	87.1^{b}	90.8^{b}
Fe	1857.2^{a}	1456.2^{b}	1560.3^{b}	1256.9^{c}
∑	2030.3^{a}	1587.1^{b}	1689.5^{b}	1587.1^{c}

explanations as in Table 2

CONCLUSIONS

1. The application of MSF in autumn increased the content of Cu, Zn and Fe and decreased the concentration of Mn in the leaf rosettes of winter oilseed rape. The application of MSF during sowing increased Zn, Mn and Fe levels in roots before winter dormancy. The observed changes in the micronutrient content of rosettes and roots in autumn were influenced by the dose of the NPK fertilizer applied to the soil surface.

2. MSF improved the micronutrient uptake by winter oilseed rape plants in autumn.

3. MSF increased micronutrient concentrations in the seeds (Cu, Mn and Fe) and straw (Cu, Zn, Mn and Fe) of winter oilseed rape. In the treatments where the NPK fertilizer was applied before sowing (at the standard or half the standard dose), the application of MSF during sowing decreased Cu and Mn concentrations and increased the Zn and Fe content of roots.

4. The seeds and straw of winter oilseed rape accumulated significantly more micronutrients (Cu, Zn, Mn and Fe) in response to MSF. The application of MSF in autumn decreased micronutrient uptake by roots by approximately 17-22%.

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