Journal of Elementology ISSN 1644-2296

Radawiec A., Szulc W., Rutkowska B. 2021.
Effect of fertilization with selenium on the content of selected microelements in spring wheat grain.
J. Elem., 26(4): 1025-1036. DOI: 10.5601/jelem.2021.26.4.2206

RECEIVED: 28 October 2021
ACCEPTED: 25 November 2021

ORIGINAL PAPER

EFFECT OF FERTILIZATION WITH SELENIUM ON THE CONTENT OF SELECTED MICROELEMENTS IN SPRING WHEAT GRAIN*

Aleksandra Radawiec, Wiesław Szulc, Beata Rutkowska

Independent Department of Agricultural Chemistry
Warsaw University of Life Sciences, Warsaw, Poland

Abstract

Microelements are important components of living organisms. Their small amounts fulfil substantial functions in organisms, although in larger amounts they can have a toxic effect. The research presented in the paper addressed the effect of different methods of fertilization with selenium at different stages of plant growth on the content of selenium, iron, zinc, copper and manganese in the grain of spring wheat (*Triticum aestivum* L.). Foliar fertilization (dose 5 g ha^{-1}), seed (dose 50.00 µmol) and foliar, soil (dose 5 g ha^{-1}) and foliar, as well as seed, soil and foliar fertilization were introduced. The content of selenium, Se, Fe, Zn and Mn in the grain was determined after mineralization in a mixture of HNO_3 and $HClO_4$, through the method of atomic absorption spectrometry (AAS). The study results show that fertilization with selenium has no effect on the yielding of spring wheat. It contributes, however, to an increase in the selenium content in the grain. Fertilization to the grain and soil with additional foliar application at the tillering and stem elongation stage (G+S+F1-2), as well as soil fertilization combined with foliar application at the same stages (S+F1-2) and the stem elongation stage alone (S+F2) proved the most effective. The best period for selenium application in cultivation of spring wheat is therefore the stem elongation stage (BBCH 30–39). Fertilization with selenium did not contribute to an increase in the content of the remaining selected microelements in the grain of spring wheat. The values of the analysed elements are comparable with natural amounts occurring in crops. This shows that fertilization with selenium permits an increase in its content in the grain of spring wheat with no excessive toxic accumulation of elements, such as iron, copper, zinc, or manganese.

Keywords: Se application, Triticum aestivum, iron, zinc, copper, manganese.

Aleksandra Radawiec, Independent Department of Agricultural Chemistry, Institute of Agriculture and Ecology, Warsaw University of Life Sciences, Nowoursynowska 166, 02-787 Warsaw, Poland, aleksandra_kowalczyk@sggw.edu.pl
* This research received no external funding.

INTRODUCTION

Microelements are important components of plants. In small quantities, they determine balanced metabolism, growth, and reproduction. As the first link in the food chain, plants provide them to consumers of all levels, including humans. Microelements are of key importance in a diet, and translate into the state of health of the population. One of element is selenium, considered an element vital for animals and humans. It participates in antioxidant processes, is included in the composition of the thyroid hormone, regulates the functioning of the immune system, and protects the brain and reproductive organs (Ratajczak, Gietka-Czernel 2016).

Despite the great importance of selenium, in many countries around the globe, the supply of the element is too low in comparison to the recommended consumption. There is a significant relationship between the Se content in soil and the content in plants (Liu et al. 2021). Soil is the main source of nutrients influencing the yield of plants (Vilček, Torma, 2016) and their elemental composition (Cacak-Pietrzak et al. 2019). The optimum dose of Se for adults varies from 50 to 200-400 µg per day (Vinceti et al. 2018), and its consumption is lower in the majority of European countries (Stoffaneller, Morse, 2015). Selenium deficiency in human organisms results in many unfavourable symptoms (Langauer-Lewowicka, Pawlas 2016). In China, in areas poor in Se, diseases related to selenium deficit are observed, namely the Kashin-Beck disease and the Keshan disease (Shreenath et al. 2018). Counteracting such phenomena involves various activities aimed at an increase in the dietary selenium content. One measure is fertilization with the element (Chilimba et al. 2012, Alfthan et al. 2015, Izydorczyk et al. 2021).

Plants, and particularly crops, have the ability of accumulating and metabolizing selenium, therefore constituting one of the main selenium sources in the cells of mammals (Combs 2015). Although the element is believed to fulfil no important functions for plants, many studies have revealed a positive effect of low selenium contents on plants (Ramos et al. 2010, Chauhan et al. 2017, Molnár et al. 2018).

Considering the effect of selenium on plant metabolism, relatively few papers discuss its effect on the accumulation of other elements, such as manganese (Mn), copper (Cu), zinc (Zn), and iron (Fe). Small quantities of these elements are vital for plants as well as humans, and their insufficient supply may contribute to a reduction of crop yields and negative health effects in the population (Silva et al. 2018).

The objective of the study was to determine the effect of diversified fertilization with selenium on the accumulation of microelements, such as Zn, Fe, Cu, and Mn, in the grain of spring wheat *Triticum aestivum* L.

MATERIALS AND METHODS

The research was conducted in 2018-2020 at the Experimental Station of the Institute of Agriculture of the Warsaw University of Life Sciences in Skierniewice in the form of a field trial. Weather conditions are presented in Figures 1 and 2. These conditions are typical for central Poland.

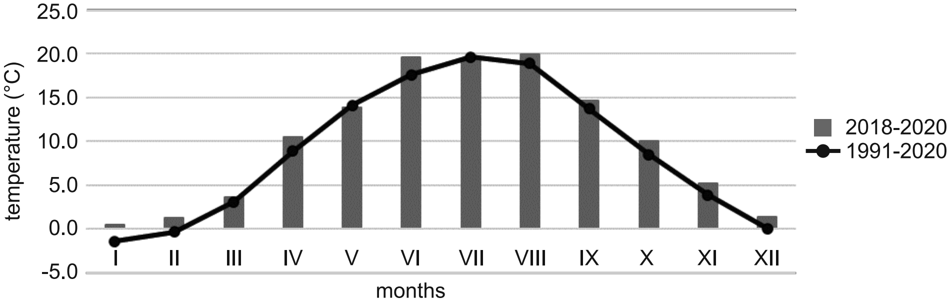

Fig. 1. Monthly temperature in 2018-2020 against the background of many years 1991-2020

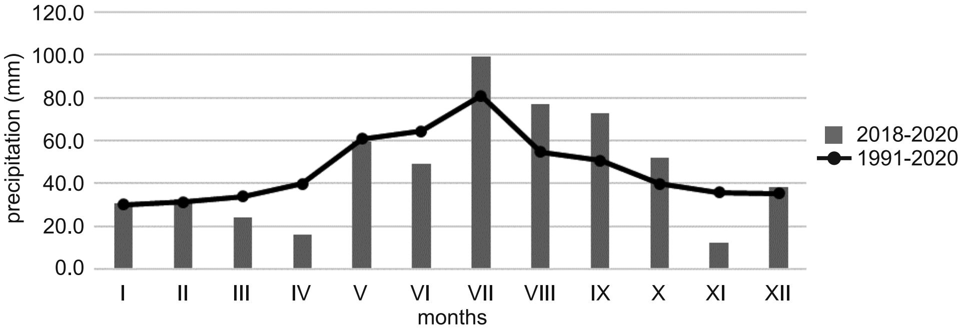

Fig. 2. Monthly precipitation totals in 2018-2020 against the background of many years 1991-2020

The experiment was carried out on light, sandy soil, on experimental plots with an area of 16.5 m^2. The pH of the soil determined in 1-mol KCl by the potentiometric method on an automatic pH meter (Moga, Poland) was 4.97. This is a typical value for over half of the soils in Poland. Total content of nitrogen in soil by the Kjeldahl method was 0.76 g kg^{-1}, carbon determined on a Vario Max analyzer (Elementar, Germany) was 8.40 g kg^{-1}, and sulphur determined by the same method was 0.33 g kg^{-1}, phosphorus determined by the Egner-Riehm method was 45.57 mg kg^{-1}, and potassium determined by the same method was 150 mg kg^{-1}. Total selenium content in the soil was determined by mineralization in aqua regia, then determined by atomic absorption spectrometry (AAS) using a Thermo Electronic Solaar M6 (Thermo Scientific, Wilmington, NC, USA). Selenium content in soil was 0.128 mg kg^{-1}.

The plant used for the study was spring wheat *Triticum aestivum* L., the cv. Mandaryna. The sowing was done with a Poznaniak seeder. The seeding density was 5 million grains per ha.

Selenium was introduced in the form of sodium selenate (Na_2SeO_4). The following types of fertilization with selenium were applied: 1) foliar application (F), 2) seed (G) and foliar (F) application, 3) soil (S) and foliar (F) application, 4) seed (G), soil (S) and foliar (F) application. Foliar application was dosed at a concentration of 16.66 mg Se l^{-1}, which means 5.00 g Se ha^{-1} (spraying volume per hectare was 300 L), at different development growth stages of the plant: F1 – tillering (BBCH 22), F2 – stem elongation (BBCH 32), F3 – inflorescence emergence (BBCH 52), and F4 – ripening (BBCH 85). Moreover, foliar fertilization treatments were applied at several development stages combined, where the total fertilizer dose (5.00 g Se ha^{-1}) was divided into a number of selenium applications: F1-2 – tillering and stem elongation, F1-3 – tillering, stem elongation, and inflorescence emergence, as well as F1-4 – tillering, stem elongation, inflorescence emergence, and ripening stage (Table 1). Seed application was performed through soaking spring wheat grains in 50.00 μmol selenium solution for 24 h before seeding. Soil fertilization at a dose of 5.00 g Se ha^{-1} was applied before wheat seeding (spraying volume per hectare: 300 dm^3). The experiment was conducted in three replications.

The content of selenium, zinc, iron, copper and manganese in the grain was determined after mineralization in a mixture of HNO_3 and $HClO_4$, through the method of atomic absorption spectrometry (AAS), using a Thermo Elemental Solaar M6 apparatus (Thermo Scientific, Wilmington, NC, USA).

The statistical analyses were performed by means of the Statgraphics 5.1. software (The Plains, Virginia, USA). The results were subject to single factor and multivariate analysis of variance ANOVA and *t*-test at a significance level of p= 0.05, and Pearson linear correlation analysis.

RESULTS AND DISCUSSION

In the control sample, the grain yield was 2.19 t ha^{-1} (Figure 3). Objects fertilized with selenium generated both higher and lower yield in comparison with control, although these differences were not significant. A significantly higher grain yield was found only in the case of soil fertilization together with foliar application in the tillering phase (S+F1). Different fertilization methods and different selenium doses generally had no effect on the yield of the grain of spring wheat. Other studies have also shown that fertilization with selenium, even in higher doses such as 5-20 g ha^{-1} Se, and even up to g ha^{-1} Se, causes no decrease in the yield (Ramkissoon 2020).

Selenium content in the grain of spring wheat in the control sample was 0.161 mg kg^{-1} (Table 2). It was the lowest value. The low selenium content

Table 1

Research design

Treatment		Dose of Se	Total dose of Se
Control	**C**	0.00 g ha^{-1}	0.00 g ha^{-1}
Foliar application	**F1**	5.00 g ha^{-1}	5.00 g ha^{-1}
	F2	5.00 g ha^{-1}	5.00 g ha^{-1}
	F3	5.00 g ha^{-1}	5.00 g ha^{-1}
	F4	5.00 g ha^{-1}	5.00 g ha^{-1}
	F1-2	2.50 g ha^{-1} in each treatment	5.00 g ha^{-1}
	F1-3	1.67 g ha^{-1} in each treatment	5.00 g ha^{-1}
	F1-4	1.25 g ha^{-1} in each treatment	5.00 g ha^{-1}
Seed and foliar application	**G**	50.00 μmol grain	50.00 μmol
	G+F1	50.00 μmol grain + 5.00 g ha^{-1} foliar	50.00 μmol + 5.00 g ha^{-1}
	G+F2	50.00 μmol grain + 5.00 g ha^{-1} foliar	50.00 μmol + 5.00 g ha^{-1}
	G+F3	50.00 μmol grain + 5.00 g ha^{-1} foliar	50.00 μmol + 5.00 g ha^{-1}
	G+F4	50.00 μmol grain + 5.00 g ha^{-1} foliar	50.00 μmol + 5.00 g ha^{-1}
	G+F1-2	50.00 μmol grain + 2.5 g ha^{-1} foliar in each treatment	50.00 μmol + 5.00 g ha^{-1}
	G+F1-3	50.00 μmol grain + 1.67 g ha^{-1} foliar in each treatment	50.00 μmol + 5.00 g ha^{-1}
	G+F1-4	50.00 μmol grain + 1.25 g ha^{-1} foliar in each treatment	50.00 μmol + 5.00 g ha^{-1}
Soil and foliar application	**S**	5.00 g ha^{-1}	5.00 g ha^{-1}
	S+F1	5.00 g ha^{-1} soil + 5.00 g ha^{-1} foliar	10.00 g ha^{-1}
	S+F2	5.00 g ha^{-1} soil + 5.00 g ha^{-1} foliar	10.00 g ha^{-1}
	S+F3	5.00 g ha^{-1} soil + 5.00 g ha^{-1} foliar	10.00 g ha^{-1}
	S+F4	5.00 g ha^{-1} soil + 5.00 g ha^{-1} foliar	10.00 g ha^{-1}
	S+F1-2	5.00 g ha^{-1} soil + 2.50 g ha^{-1} foliar in each treatment	10.00 g ha^{-1}
	S+F1-3	5.00 g ha^{-1} soil + 1.67 g ha^{-1} foliar in each treatment	10.00 g ha^{-1}
	S+F1-4	5.00 g ha^{-1} soil + 1.25 g ha^{-1} foliar in each treatment	10.00 g ha^{-1}
Seed, soil and foliar application	**G+S**	50.00 μmol grain + 5.00 g ha^{-1} soil	50.00 μmol + 5.00 g ha^{-1}
	G+S+F1	50.00 μmol grain + 5.00 g ha^{-1} soil + 5.00 g ha^{-1} foliar	50.00 μmol + 10.00 g ha^{-1}
	G+S+F2	50.00 μmol grain + 5.00 g ha^{-1} soil + 5.00 g ha^{-1} foliar	50.00 μmol + 10.00 g ha^{-1}
	G+S+F3	50.00 μmol grain + 5.00 g ha^{-1} soil + 5.00 g ha^{-1} foliar	50.00 μmol + 10.00 g ha^{-1}
	G+S+F4	50.00 μmol grain + 5.00 g ha^{-1} soil + 5.00 g ha^{-1} foliar	50.00 μmol + 10.00 g ha^{-1}
	G+S+F1-2	50.00 μmol grain + 5.00 g ha^{-1} soil + 2.50 g ha^{-1} foliar in each treatment	50.00 μmol + 10.00 g ha^{-1}
	G+S+F1-3	50.00 μmol grain + 5.00 g ha^{-1} soil + 1.67 g ha^{-1} foliar in each treatment	50.00 μmol + 10.00 g ha^{-1}
	G+S+F1-4	50.00 μmol grain + 5.00 g ha^{-1} soil + 1.25 g ha^{-1} foliar in each treatment	50.00 μmol + 10.00 g ha^{-1}

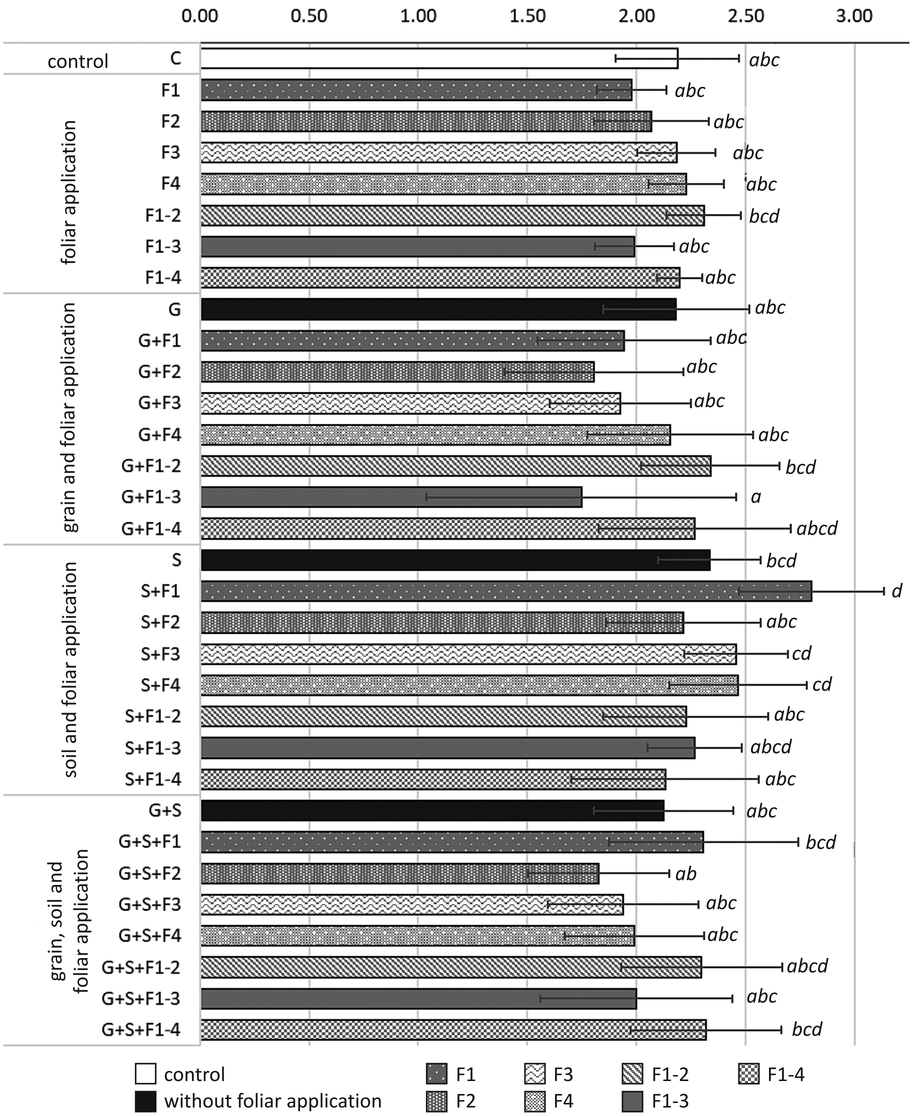

Fig. 3. Average yield depending on fertilization.
Results show means and standard deviations (n=9): *A*, *b*, *c* – means followed by the same letter are not significantly different from one another based on the Tukey's test at $p \leq 0.05$.

in the control sample of the spring wheat grain was correlated with its low content in the soil, considered as deficient. When such low selenium levels are determined in soil and plants, measures aimed at counteracting the phenomenon are implemented in many countries (Zapletalová et al. 2021). Spring wheat fertilized with selenium in all combinations was characterized by a higher content of this element in the grain. This content was deter-

Table 2

Content of selenium, copper, zinc, iron and manganese in grain (mg kg^{-1})

Treatment		Se	Cu	Zn	Fe	Mn
Control	C	0.16±0.01^{a}	4.07±0.42^{abcde}	66.79±3.02^{d}	44.89±4.11^{a}	38.05±6.24^{cde}
Foliar application	F1	0.28±0.11^{abcd}	3.75±0.25^{abcde}	40.80±1.50^{ab}	45.95±5.36^{a}	32.14±2.13^{abcde}
	F2	0.31±0.06^{abcd}	3.91±0.10^{abcde}	66.76±5.75^{d}	29.17±4.61^{a}	37.57±3.99^{bcde}
	F3	0.26±0.11^{abc}	4.08±0.84ab^{cde}	46.83±6.43^{abcd}	27.48±0.51^{a}	32.15±5.97^{abcde}
	F4	0.23±0.07^{ab}	3.36±0.31^{abc}	36.11±1.21^{a}	25.72±2.32^{a}	29.27±4.73^{abc}
	F1-2	0.38±0.15^{abcde}	3.75±0.40^{abcde}	56.28±6.50^{abcd}	47.41±4.74^{a}	34.07±2.20^{abcde}
	F1-3	0.42±0.16^{bcdef}	3.81±0.44^{abcde}	63.57±3.83^{cd}	28.49±1.52^{a}	32.22±6.72^{abcde}
	F1-4	0.28±0.13^{abcd}	3.87±0.23^{abcde}	49.42±5.13^{abcd}	35.79±2.95^{a}	38.47±4.50^{de}
Seed and foliar application	G	0.23±0.10^{ab}	4.10±0.08^{abcde}	43.91±5.20^{abc}	42.70±5.08^{a}	33.40±3.22^{abcde}
	G+F1	0.23±0.12^{ab}	4.79±0.56^{e}	52.48±6.45^{abcd}	31.18±0.16^{a}	35.22±1.94^{abcde}
	G+F2	0.30±0.12^{abcd}	4.24±0.49^{bcde}	58.66±6.52^{bcd}	32.33±3.76^{a}	40.01±5.81^{e}
	G+F3	0.26±0.11^{abc}	3.86±0.04^{abcde}	43.23±4.51^{ab}	25.67±3.16^{a}	33.93±3.74^{abcde}
	G+F4	0.21±0.07^{ab}	3.78±0.35^{abcde}	46.83±5.73^{abcd}	26.89±4.75^{a}	33.67±6.35^{abcde}
	G+F1-2	0.35±0.09^{abcde}	3.78±0.15^{abcde}	40.87±3.59^{ab}	28.31±3.46^{a}	38.45±4.10^{de}
	G+F1-3	0.30±0.12^{abcd}	3.64±0.51^{abcd}	50.08±7.73^{abcd}	27.51±5.43^{a}	35.14±4.52^{abcde}
	G+F1-4	0.23±0.11^{ab}	4.37±0.23^{cde}	42.21±0.86^{ab}	29.28±5.34^{a}	36.87±1.68^{bcde}
Soil and foliar application	S	0.36±0.03^{abcde}	4.54±0.18^{de}	50.59±8.91^{abcd}	28.74±3.08^{a}	32.70±7.31^{abcde}
	S+F1	0.28±0.02^{abcd}	3.98±0.20^{abcde}	50.21±5.20^{abcd}	32.17±3.58^{a}	33.89±7.99^{abcde}
	S+F2	0.64±0.08^{fgh}	3.64±0.30^{abcd}	50.51±4.21^{abcd}	31.19±6.01^{a}	32.17±2.15^{abcde}
	S+F3	0.32±0.05^{abcd}	3.06±0.46^{a}	45.36±5.62^{abc}	45.76±2.47^{a}	29.49±5.41^{abc}
	S+F4	0.28±0.02^{abcd}	3.72±0.57^{abcde}	42.08±7.33^{ab}	27.88±1.50^{a}	26.60±1.95^{a}
	S+F1-2	0.71±0.14^{gh}	3.17±0.37^{ab}	40.92±1.80^{ab}	27.58±3.80^{a}	28.80±2.20^{ab}
	S+F1-3	0.50±0.17^{defg}	3.25±0.44^{abc}	47.59±3.99^{abcd}	30.24±3.82^{a}	30.69±3.86^{abcd}
	S+F1-4	0.26±0.11^{abc}	3.73±0.84^{abcde}	45.63±7.01^{abc}	36.39±6.64^{a}	34.13±6.28^{abcde}
Seed, soil and foliar application	G+S	0.38±0.13^{abcde}	3.93±0.10^{abcde}	45.40±7.47^{abc}	47.86±2.78^{a}	34.06±7.89^{abcde}
	G+S+F1	0.34±0.10^{abcde}	3.83±0.31^{abcde}	41.15±3.54^{ab}	27.17±4.17^{a}	32.26±2.23^{abcde}
	G+S+F2	0.56±0.21^{efgh}	4.18±0.98^{abcde}	60.52±5.72^{bcd}	36.93±4.87^{a}	39.95±5.47^{e}
	G+S+F3	0.32±0.11^{abcd}	3.52±0.43^{abcd}	44.24±3.30^{abc}	26.89±5.26^{a}	30.06±3.50^{abcd}
	G+S+F4	0.34±0.12^{abcde}	4.15±0.58^{abcde}	47.22±1.84^{abcd}	29.52±1.13^{a}	29.84±4.76^{abcd}
	G+S+F1-2	0.74±0.16^{h}	3.66±0.29^{abcde}	40.96±5.52^{ab}	40.29±2.85^{a}	35.88±5.45^{bcde}
	G+S+F1-3	0.47±0.15^{cdef}	3.30±0.22^{abc}	53.23±4.02^{abcd}	26.84±3.00^{a}	33.06±6.20^{abcde}
	G+S+F1-4	0.28±0.13^{abcd}	3.63±0.20^{abcd}	44.86±3.17^{abc}	34.03±5.34^{a}	35.06±4.19^{abcde}

Results show means and standard deviations (n=9): *a*, *b*, *c* – means followed by the same letter are not significantly different from one another based on the Tukey's test at $p \le 0.05$.

mined by both the fertilization method and development stage at which foliar fertilization was applied. The highest selenium content was recorded in wheat grain of wheat fertilized with Se as seed, soil and foliar application at the tillering and stem elongation stage (G+S+F1-2), where the content reached 0.74 mg kg^{-1} Se. Despite the application of different selenium doses, no excessive toxic accumulation of the element in the plant was recorded that could be a threat for animals or humans, constituting further links in the trophic chain (Radawiec et al. 2021).

The results also show that the stage at which selenium was applied also has a significant effect on the final content of the element in the grain of spring wheat. Despite the application of the same dose of selenium within a single fertilization method, whether foliar (F), soil (S), seed (G), or combined application (S+G), the introduction of selenium at different stages of development of wheat translated into different Se contents in the grain. The study showed that the best period for the application of selenium in cultivation of spring wheat is the stem elongation stage (BBCH 30-39), as confirmed by other experiments (Radawiec et al. 2021, Ramkissoon 2021).

Zinc content in the control sample was 66.79 mg kg^{-1}, and was the highest (Table 2). Equally high content was recorded in the grain of wheat fertilised with Se by foliar application at the stage of stem elongation (F2) and in the case of foliar fertilization at the tillering, stem elongation, and inflorescence emergence stages (F1-3). Same as zinc, the iron content in the control sample was among the highest, reaching 44.89 mg kg^{-1} Fe. Comparably high contents of the element were determined after foliar application at the tillering stage (F1), at the tillering and stem elongation stage (F1-2), and for seed fertilization (G), soil fertilization with foliar application at the stage of inflorescence emergence (S+F3), and seed and soil fertilization (G+S). Copper content was also determined in the grain of spring wheat. In the control sample, it was 4.07 mg kg^{-1} Cu. The highest content of the element was obtained after seed fertilization combined with foliar application at the stem elongation stage (G+F1). Soil (S) and seed fertilization combined with foliar application at the stages of stem elongation, tillering, inflorescence emergence, and ripening (G+F1-4) proved equally effective. Manganese content in the grain of spring wheat was shaped similarly as in the case of copper. In the control sample, it reached 38.05 mg kg^{-1} Mn, and varied from 26.60 mg kg^{-1} to 40.01 mg kg^{-1} in the grain of spring wheat fertilized with selenium. The highest content of the element was recorded after seed fertilization combined with foliar application at the stage of stem elongation (G+F2), and after seed and soil fertilization with foliar application at the stage of stem elongation (G+S+F2). Fertilization with selenium had no considerable effect on the accumulation of microelements. Content of iron, copper, and manganese did not significantly differ from that in the control sample. The greatest variability was noted in relation to the zinc content in grain.

The comparison of the results with other studies points to the general conclusion that fertilization with selenium can cause lack or a slight decrease in the content of microelements in the grain of spring wheat (Filek et al. 2010, Tobiasz et al. 2014, Zapletalová et al. 2021). This tendency has no effect on the ability to accumulate selenium in wheat grain. In the study, a decrease in the content of the determined microelements usually occurred in the case of foliar application at the ripening stage (F4), and soil fertilization combined with foliar application at the stage of inflorescence emergence (S+F3) or at the ripening stage (S+F4). Therefore, foliar application of selenium at the stage of inflorescence emergence (F3) or at the ripening stage (F4) can presumably contribute to a reduction of the content of microelements in the plant.

Contents of the analysed microelements obtained as a result of fertilization with selenium were compared with natural contents occurring in plants. In our research, the content of copper in wheat grain was in the range of 3.06-4.79 mg kg^{-1}. Researchers (Kabata Pendias, Pendias 1999) determined the natural content of the element in cereals at a level of 2.6-6.0 mg kg^{-1}. The zinc content in our experiment varied from 36.11 to 66.79, and the natural content is in a range of 15-60 mg kg^{-1} Zn. In our research, we also determined the iron content. Its natural content in plants is 10-400 mg kg^{-1} Fe, while in the experiment it ranged from 25.67 mg kg^{-1} to 47.86 mg kg^{-1}. Manganese content varied in the study within a range of 26.60-40.01 mg kg^{-1}, whereas its natural content in cereal grain in Poland reaches 10-45 mg kg^{-1} Mn. Mean copper content for cereal grains in non-polluted regions is 3.7 mg kg^{-1} (Bednarek et al. 2008). Also other studies that determined contents of trace elements in cereals provide results comparable with our study (Ścigalska et al. 2011). Selenium has the ability to limit the bioassimilation of harmful elements in the food chain. It can also limit negative transformations resulting from the excess of heavy metals (Ismael et al. 2019, Shang et al. 2021). The research conducted on this subject often suggests the possibility of introducing selenium into the environment and human organisms. However, it should be borne in mind that it becomes toxic when present in excess, so possibilities of selenium distribution and possible effects of its influence should be strictly controlled. The desired target content of selenium in grains that is not toxic to living organisms ranges from 0.1 to 1.00 mg kg^{-1} Se (Bañuelos et al. 2020). For this purpose, doses of 5 to 25 g ha^{-1} Se are used (Reis et al. 2018, Ngigi et al. 2019, Xia et al. 2019). The fertilization used in the study increased the selenium content to the optimal amount recommended for enrichment with this element (Kabata Pendias, Pendias 1999, Radawiec et al. 2021). All the types and doses of fertilization presented in the study can be safely used to increase the supply of selenium in the grain without excessive accumulation of heavy metals.

CONCLUSIONS

The study results show that fertilization with selenium has no effect on the yielding of spring wheat, although it contributes to an increase in selenium content in the grain. Seed and soil fertilization with additional foliar application at the tillering and stem elongation stage (G+S+F1-2), as well as soil fertilization combined with foliar application at the same stages (S+F1-2) and at the stem elongation stage alone (S+F2) proved the most effective. Therefore, the best period for the application of selenium in cultivation of spring wheat is the stem elongation stage (BBCH 30-39). Fertilization with selenium did not contribute to an increase in the content of the remaining selected microelements in the grain of spring wheat. The determined content of the discussed elements is comparable to natural content occurring in crops. This shows that fertilization with selenium allows for an increase in its content in the grain of spring wheat with no excessive toxic accumulation of elements, such as iron, copper, zinc or manganese.

REFERENCE

ALFTHAN G., EUROLA M., EKHOLM, P., VENÄLÄINEN E.R., ROOT T., KORK-ALAINEN K., HARTIKAINEN H., SALMINEN P., HIETANIEMI V., ASPILA A. 2015. *Effects of nationwide addition of selenium to fertilizers on foods, and animal and human health in Finland: From deficiency to optimal selenium status of the population*. J. Trace Elem. Med. Biol., 31: 142-147. DOI: 10.1016/ /j.jtemb.2014.04.009

BAÑUELOS G.S., FREEMAN J., ARROYO I. 2020. *Accumulation and speciation of selenium in biofortified vegetables grown under high boron and saline field conditions*. Food Chem. X, 5:100073. DOI: 10.1016/j.fochx.2019.100073

BEDNAREK W., TKACZYK P., DRESLER S. 2008. *The content of heavy metals as a criterion for assessing the quality of winter wheat grain*. Acta Agrophys. 12: 315-326. (in Polish) http://www.acta-agrophysica.org/Heavy-metals-contents-as-a-criterion-for-assessment-of-winter-wheat- -grain-quality,107476,0,2.html

CACAK-PIETRZAK G., PODLESNA A., CEGLINSKA A. 2019. *Influence of soil type and fertilization on yielding, physical properties and chemical composition of spring wheat grain*. Grain Milling Review, 63:28-32. (in Polish)

CHAUHAN R., AWASTHI S., TRIPATHI P., MISHRA S., DWIVEDI S., NIRANJAN A., MALICK S., TRIPATHI P., PANDE V., TRIPATHI R.D. 2017. *Selenite modulates the level of phenolics and nutrient element to alleviate the toxicity of arsenite in rice (Oryza sativa* L.*)*. Ecotoxicol. Environ. Saf., 138: 47-55. DOI: 10.1016/j.ecoenv.2016.11.015

CHILIMBA A.D., YOUNG S.D., BLACK C.R., MEACHAM M.C., LAMMEL J., BROADLEY M. 2012. *Agronomic biofortification of maize with selenium (Se) in Malawi*. Field Crops Res., 125: 118-128. DOI: 10.1016/j.fcr.2011.08.014

COMBS JR F. 2015. *Biomarkers of selenium status*. Nutrients, 7: 2209-2236. DOI: 10.3390/ /nu7042209

FILEK M., ZEMBALA M., KORNAŚ A., WALAS S., MROWIEC H., HARTIKAINEN H. 2010. *The uptake and translocation of macro-and microelements in rape and wheat seedlings as affected by selenium supply level*. Plant Soil, 336: 303-312. DOI: 10.1007/s11104-010-0481-4

ISMAEL M.A., ELYAMINE A.M., MOUSSA M.G., CAI M., ZHAO X., HU C. 2019. *Cadmium in plants:*

uptake, toxicity, and its interactions with selenium fertilizers. Metallomics, 11: 255-277. DOI: 10.1039/c8mt00247a

Izydorczyk G., Ligas B., Mikula K., Witek-Krowiak A., Moustakas K., Chojnacka K. 2021. *Biofortification of edible plants with selenium and iodine – a systematic literature review*. Sci. Total Environ, 754: 141983. DOI: 10.1016/j.scitotenv.2020.141983

Kabata-Pendias A., Pendias H. 1999. *Biogeochemistry of trace elements*. PWN, Warszawa, Poland.

Langauer-Lewowicka H., Pawlas K. 2016. *Selenium in the environment*. Environ Med, 19: 9-16. (in Polish)

Liu H., Wang X., Zhang B., Han Z., Wang W., Chi Q., Zhou J., Nie L., Xu S., Liu D. 2021. *Concentration and distribution of selenium in soils of mainland China, and implications for human health*. J. Geochem. Explor., 220: 106654. DOI: 10.1016/j.gexplo.2020.106654

Molnár Á., Kolbert Z., Kéri K., Feigl G., Ördög A., Szőllősi R., Erdei L. 2018. *Selenite-induced nitro-oxidative stress processes in Arabidopsis thaliana and Brassica juncea*. Ecotoxicol. Environ. Saf., 148: 664-674. DOI: 10.1016/j.ecoenv.2017.11.035

Ngigi P.B., Lachat C., Masinde P.W., Du Laing G. 2019. *Agronomic biofortification of maize and beans in Kenya through selenium fertilization*. Environ. Geochem. Health, 41: 2577-2591. DOI: 10.1007/s10653-019-00309-3

Printz B., Lutts S., Hausman J. F., Sergeant K. 2016. *Copper trafficking in plants and its implication on cell wall dynamics*. Front. Plant Sci., 7: 601. DOI: 10.3389/fpls.2016.00601

Radawiec A., Szulc W., Rutkowska B. 2021. *Selenium biofortification of wheat as a strategy to improve human nutrition*. Agriculture, 11(2): 144. DOI: 10.3390/agriculture11020144

Ramkissoon C. 2020. *Selenium dynamics in cereal biofortification: optimising fertiliser strategies and assessing residual fate*. Ph.D. Thesis, University of Adelaide, Adelaide, Australia. https://digital.library.adelaide.edu.au/dspace/handle/2440/126970

Ramos S.J., Faquin V., Guilherme L.R.G., Castro E.M., Ávila F.W., Carvalho G.S., Bastos C.E.A., Oliveira C. 2010. *Selenium biofortification and antioxidant activity in lettuce plants fed with selenate and selenite*. Plant Soil Environ, 56(12): 584-588. DOI: 10.17221/113/2010-PSE

Ratajczak M., Gietka-Czernel M. 2016. *The role of selenium in the human body*. Adv Med Sci, 12: 929-933. (in Polish) http://www.czytelniamedyczna.pl/5868,rola-selenu-w-organizmie-czlowieka.html

Reis H.P.G., Barcelos J.P.Q., Junior E.F., Santos E.F., Silva V.M., Moraes M.F., Putti F.F., Reis A.R. 2018. *Agronomic biofortification of upland rice with selenium and nitrogen and its relation to grain quality*. J. Cereal Sci., 79: 508-515. DOI: 10.1016/j.jcs.2018.01.004

Shang X., Yu P., Yin Y., Zhang Y., Lu Y., Mao Q., Li Y. 2021. *Effect of selenium-rich Bacillus subtilis against mercury-induced intestinal damage repair and oxidative stress in common carp*. Comp. Biochem. Physiol. Part C: Toxicol Pharmacol, 239: 108851.75. DOI: 10.1016/j.cbpc.2020.108851

Shreenath A. P., Ameer M. A., Dooley J. 2018. *Selenium deficiency*. StatPearls Publishing 2018. https://europepmc.org/article/nbk/

Silva C.S., Moutinho C., Ferreira da Vinha A., Matos C. 2019. *Trace minerals in human health: Iron, zinc, copper, manganese and fluorine*. Int J Sci Res Methodol, 13: 57-80. https://bdigital.ufp.pt/handle/10284/8105

Stoffaneller R., Morse N. L. 2015. *A review of dietary selenium intake and selenium status in Europe and the Middle East*. Nutrients, 7: 1494-1537. DOI: 10.3390/nu7031494

Ścigalska B., Puła J., Łabuz B. 2011. *The content of trace elements in the grain of triticale grown in crop rotation and grain monocultures*. Fragm. Agron., 28: 112-119.

Tobiasz A., Walas S., Filek M., Mrowiec H., Samsel K., Sieprawska A., Hartikainen H. 2014.

Effect of selenium on distribution of macro-and micro-elements to different tissues during wheat ontogeny. Biol Plant, 58(2): 370-374. DOI: 10.1007/s10535-014-0407-8

Vilček J., Torma S. 2016. *Winter wheat (Triticum aestivum* L.*) growth potential in the Slovak rural landscape*. Arch Agron Soil Sci, 62: 235-245. DOI: 10.1080/03650340.2015.1043899

Vinceti M., Filippini T., Wise L.A. 2018. *Environmental selenium and human health: An update*. Curr. Environ. Health Rep., 5: 464-485. DOI: 10.1007/s40572-018-0213-0

Xia Q., Yang Z.P., Xue N.W., Dai X.J., Zhang X., Gao Z.Q. 2019. *Effect of foliar application of selenium on nutrient concentration and yield of colored-grain wheat in China*. Appl. Ecol. Environ. Res., 17: 2187-2202. DOI: 10.15666/aeer/1702_21872202

Zapletalová A., Ducsay L., Slepčan M., Vicianová M., Hozlár P., Bušo R. 2021. *Selenium effect on wheat grain yield and quality applied in different growth stages*. Plant Soil Environ, 67(3): 147-153. DOI: 10.17221/589/2020-PSE