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Effect of fertilizer application on yield and elemental composition of maize in the western region of Ukraine

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ABSTRACT

The results of the study on the effect of fertilization on the productivity and elemental composition of maize plants in the Precarpathian region of Ukraine are presented. Application of the mineral fertilizer $N_{90}P_{90}K_{90}$ significantly increased yield – on average up to 5.74 t/ha, which is + 0.93 t/ha or +19.3% compared to the control. This was the most effective treatment among all those studied. It was found that the highest phosphorus and potassium contents in maize leaves and roots were observed in the variant with the application of Intermag Titan. The treatments with mineral fertilizers and humates showed intermediate values. This indicates that titanium fertilizer promotes the uptake of phosphorus and potassium by maize plants from the soil, while humates are a strong source of potassium. Under the application of mineral fertilizer at $N_{90}P_{90}K_{90}$, the potassium content was the highest, amounting to 1205 mg/100 g in leaves, 1362 mg/100 g in stems, and 725 mg/100 g in grains. It is worth noting that in maize leaves, the highest aluminium content (96 mg/100 g) was recorded with the application of mineral fertilizers, while the other three treatments showed approximately the same level. The highest calcium content was observed in the treatment with Intermag Titan (1557 mg/100 g), whereas the lowest calcium levels were recorded in the mineral fertilizer treatment (824 mg/100 g) and in the control (830 mg/100 g). However, these two treatments demonstrated the highest zinc content – 1182 and 358 mg/100 g, respectively, which is 98% higher compared to treatments 3 and 4. The chromium content in maize roots was the highest in the treatment with the application of Black Jack KS (58 mg/100 g), which was almost ten times greater compared to the plants in the other treatments. This result can be explained by its application in combination with fertilizers.

Keywords: maize, yield, grain, leaves, stems, roots, fertilization, macroelements and microelements.

INTRODUCTION

Sweet maize (*Zea mays saccharata* Sturt.) is an annual plant belonging to the Poaceae family. Today, maize ranks among the leading cereal crops (Pashchenko et al., 2009; Zynchenko, 2013; Hadzalo et al., 2016; Hryhoriv et al., 2021; Hryhoriv et al., 2022). The world leader in the production and consumption of sweet maize is the United States, where sweet maize is considered a "national" product. Large areas under this crop are also found in France, Hungary, and Thailand. In recent years, sweet maize and its processed products have become increasingly popular and widespread in Ukraine. Its grains are used in food in freshly cooked, frozen, and canned form and contain 18.6–23.4% sugar and 47–51% starch (Hryhoriv et al., 2020; Karpenko et al., 2022).

The growing demand for sweet maize is largely due to the high quality of the product. In terms of nutritional properties, sweet maize is the leader among vegetables. Its grains in the milky ripeness phase contain vitamins B1, B2, B3, B6, C, E, PP, carotene, and other biologically active substances. The valuable components of sweet maize grains also include trace elements such as selenium, chromium, zinc, copper, nickel, and iron.

Maize grain productivity is the result of the combined effect of technological factors, in particular the choice of varietal material, fertilization systems, the use of plant protection products, and the specific climatic conditions of the growing region. In recent years, Ukraine has seen a significant increase in the yield of this crop–from 6.0 to 10.0 t/ha – due to improvements in agricultural technology and adaptation to changing climatic conditions. At the same time, the profitability of maize production largely depends on the effectiveness of the technological measures applied, which necessitates further research on the optimization of agrotechnical elements (Kolisnichenko et al., 2025).

Providing plants with nutrients is an effective, and sometimes decisive, factor that not only increases yield, but also improves the quality of maize grain. At the same time, metabolic processes change, and beneficial substances accumulate in plants more actively - proteins, fats, carbohydrates, etc. The fertilizer system provides an average of 40–60% of the growth of any crop, including maize (Lokot et al., 2019; Hlyva et al., 2022; Palamarchuk, 2019; Palamarchuk et al., 2022; Stepanenko, 2024).

Growing high-quality, high-yielding crops, including maize, depends on a balanced supply of nutrients (Sahrawat et al., 2008; Prokeš, 2008). In this respect, nitrogen is crucial, especially for increasing crop yields and feed production (Berenguer et al., 2009; Gallais et al., 2008). Nitrogen is often the only nutrient supplied with fertilizers, and crops in many cases depend on the natural fertility of the soil as a source of other macronutrients – P, K, Ca, Mg, S (Lošák et al., 2010). One of the most important cationic minerals for vegetative plant growth is potassium, which directly affects yield and product quality (Daoud et al. 2020).

Modern agricultural production requires improving approaches to agrochemical support of agriculture and rational use of resources through monitoring the condition of plants during the growing season. In this context, plants serve as a kind of indicator, and the content of chemical elements reflects the conditions of their provision with nutrients during ontogenesis (Chaban et al., 2014; Chaban et al., 2014).

Dry maize grain contains 9–12% protein, 4–6% fat and 65–70% nitrogen-free extractives, which makes it a valuable concentrated feed for all farm animals and poultry. One kilogram of this grain is equivalent to 1.34 feed units and contains 70 g of digestible protein. 100 kg of green mass harvested in the milky-wax ripeness phase is equal to 32 feed units, and 100 kg of dry stems harvested for grain correspond to 37 feed units and contain 1.5 kg of digestible protein (Pashchenko et al., 2009; Voloshchuk et al., 2019).

Experiments by Kastori et al. (2004) with triticale, winter wheat, peas, and maize showed that the movement of Ni, Cu, Zn, Mo, Sr, and Ba into grains was lowest in the maize variant. The assimilation of these elements by plant organs was influenced by various biotic factors (plant species, genotype, phenophase, plant part, transpiration, etc.) and abiotic factors (chemical properties and concentration of toxic substances, soil conditions, etc.) (Kastori et al., 2004).

Based on this, the aim of the research was to determine the productivity characteristics and elemental composition of maize plants and to identify possible ways to optimize their mineral nutrition.

MATERIALS AND METHODS

The research was conducted during 2022–2023 at the experimental field of the Department of Forestry and Agricultural Management, Vasyl Stefanyk Precarpathian National University. The soil of the experimental site is sod-podzolic, surface-gleyed. In terms of mechanical composition, it is a heavy clay soil with a coarse silty structure. The depth of the humus horizon is 45 cm. The agrochemical indicators are as follows: acidity (pH) – 4.7, humus content (%) – 2.7, soil nutrient content (mg/kg): nitrogen – 78.0, phosphorus – 43.0, potassium – 98.0.

The field experiment was laid out in a randomized design with three replications. The experiment studied the effect of fertilization on the productivity and elemental content in different parts of sweet maize plants. The hybrid sown was Moreland F1 (GSS 1453 F1), which is an early-maturing variety. The growing period from emergence to harvest is usually 83 days. The plant height is 2.9 m, each cob is 22 cm long and 5 cm in diameter and the plants are highly leafy.

The study examined four fertilization treatments, with the control being the variant without fertilizers (water treatment), $N_{90}P_{90}K_{90}$, Black Jack KS and Intermag Titan (Table 1).

Black Jack KS is a highly effective natural organic biostimulant. The ulmic acids and humin contained in the product act as plant growth activators by stimulating metabolic, hormonal, and enzymatic processes. Due to its full spectrum of humus components, it exhibits exceptional activity and benefits for plants when applied foliarly, distinguishing it from standard humates.

Intermag titan is a solution containing 4.5 g/l of titanium. Titanium in the fertilizer is present as a highly soluble chemical compound with an organic acid. Before plant treatment, the titanium fertilizer was diluted 250 times. Fertilizer treatments were carried out three times per season.

Dry ashing was performed for the plants at the full maturity stage at a temperature of 530 °C for 30 minutes. Ash was obtained from the roots, leaves, stems, and grain. The content of microelements (Mn, Zn, Fe, Cu, Co, Ni, Pb, Cd) in the grain and vegetative mass of maize was determined using an atomic absorption spectrophotometer S -115M1 with atomization in an air-acetylene flame.

Maize cultivation agrotechnology was generally accepted, except for the experimental treatments under investigation (Volkodav, 2001; Lebid et al., 2008).

An analysis of the meteorological conditions during the plant growing season was carried out based on data from the Ivano-Frankivsk Regional Meteorological Station. The natural and climatic conditions in 2023 differed from the multi-year average: precipitation was 199.1 mm above normal, and the average air temperature was 10.9 °C higher than the norm. During the growing season, total precipitation amounted to 607.1 mm, with the highest amounts recorded in April (116.9 mm), June (174.2 mm), and July (158.2 mm). A precipitation deficit was observed in May, where the deviation from the norm was – 28.3 mm. Particularly high temperatures were recorded in July, August, and September. The average temperature during the growing season was 17.8 °C compared to the long-term average of 16.5 °C, which is +1.3 °C higher than normal.

RESULTS AND DISCUSSION

Not only crop yield indicators determine the profitability level of agricultural production but also by the quality characteristics of the harvested products. Grain quality is formed because of the complex interaction between natural and climatic conditions, soil characteristics, and applied agrotechnologies. Fertilizer application serves as an effective tool for regulating biosynthetic processes in plants, enabling targeted formation of grain quality composition according to consumer requirements.

According to the results of the study, the lowest yield over the two-year period was observed in the control treatment (no fertilizers, water treatment) – 4.81 t/ha (Table 2). Application of the mineral fertilizer $N_{90}P_{90}K_{90}$ significantly increased yield – on average to 5.74 t/ha, which is +0.93 t/ha or +19.3% compared to the control. This was the most effective treatment among all those studied.

The use of the micronutrient fertilizer Intermag Titan resulted in a yield of 5.51 t/ha, which exceeded the control treatment by 0.70 t/ha or 14.6%. Application of Black Jack KS produced a yield of 5.46 t/ha, which was 0.65 t/ha or 13.5% higher than the control.

Thus, the application of fertilizers – both mineral and micronutrient – had a positive effect on the productivity of the Moreland F1 maize hybrid in the Precarpathian region. The greatest effect was achieved with the application of the full mineral fertilizer complex; however, the micronutrient fertilizers also demonstrated a high level of effectiveness, indicating their promise in maize nutrition systems.

Table 1. Experiment design

Maize hybrid Moreland F1	Control (no fertilizers, water treatment) $N_{90}P_{90}K_{90}$ Black Jack KS Intermag titan

Table 2. Yield of Moreland F1 maize hybrid

Treatment	Yield, t/ha			Increase compared to control	
	2023	2024	Average for two years	t/ha	%
Control	4.98	4.63	4.81	–	–
$N_{90}P_{90}K_{90}$	5.90	5.57	5.74	+0.93	+19.3%
Black Jack KS	5.61	5.32	5.46	+0.65	+13.5%
Intermag titan	5.66	5.36	5.51	+0.70	+14.6%

One of the important elements for plant growth and development, including maize, is phosphorus. This macronutrient is the basis of the plant cell's energy resources and reserves. All major biochemical processes occur with the participation of phosphorus, as it is a component of nucleic acids, nucleotides, enzymes, as well as products of photosynthesis and respiration cycles (Korovetska et al., 2009).

According to the results of the study, the highest phosphorus and potassium content in maize plant roots was observed in the Intermag Titan treatment, amounting to 114 and 2051 mg/100 g, respectively. The control treatment had the lowest values, which were 31 and 880 mg/100 g lower compared to the previous treatment (Figures 1–2).

The treatments with the application of mineral fertilizers and humates showed intermediate values, while the lowest potassium content was observed in the treatment with mineral fertilizers at the rate of $N_{90}P_{90}K_{90}$, amounting to 633 mg/100 g. This suggests that the titanium fertilizer promotes the uptake of phosphorus and potassium by maize plants from the soil, while humates are a potent source of potassium.

It was found that the phosphorus content in maize grain was almost at the same level across all treatments, whereas its highest value was observed with the application of mineral fertilizers, amounting to 725 mg/100 g.

It was found that the highest macronutrient levels in maize leaves were observed in the Black Jack KS and Intermag Titan treatments, where phosphorus content amounted to 151 and 184 mg/100 g, respectively, which is 66–72% higher compared to the control. The highest potassium content was recorded in the $N_{90}P_{90}K_{90}$ treatment, amounting to 1205 mg/100 g, which is only 75 mg/100 g more than the control, while in treatments 4 and 3 its amount was almost the same at 937–977 mg/100 g, respectively.

Potassium is one of the most important elements for plant nutrition. More than 60 enzymes are activated by potassium. It contributes to protoplasm hydration, reduces its viscosity, and increases water content. In plant cells, potassium exists in ionic form and does not become part of organic compounds, making it highly mobile, easily reutilized, and playing a key role in ion transport, water exchange, and plant osmoregulation processes (Xu et al., 2002).

The potassium content in maize stems was the lowest in plants treated with titanium fertilizer (853 mg/100 g) compared to other treatments, indicating the need to account for potassium deficiency when using titanium fertilizers. The highest potassium content in stems was observed in the mineral fertilizer treatment, amounting to 1362 mg/100 g, while the highest phosphorus content was recorded in the Black Jack KS treatment (164 mg/100 g), which is 61.6 mg/100 g more than the control.

In maize roots, the highest sulfur content was observed in the mineral fertilizer treatment at the rate of $N_{90}P_{90}K_{90}$, where it amounted to 42 mg/100 g, and the lowest was in the Black Jack KS treatment (16 mg/100 g) (Figure 3).

Calcium and silicon also play important roles in plant cell metabolism. Calcium stabilizes membranes by interacting with the negatively charged groups of phospholipids, thereby reducing their passive permeability. Almost the entire cation exchange capacity of the root surface is occupied by calcium, which limits the uptake of other ions by the plant and helps eliminate toxicity from excessive concentrations of ammonium, aluminum, manganese, and iron ions (Kots et al., 2005; Stakhiv et al., 2008). According to the study results, calcium content in maize roots ranged from 337 mg/100 g in the Black Jack KS treatment to 1279 mg/100 g in the mineral fertilizer treatment. This indicates that maize is resistant to toxic elements and can be cultivated on contaminated soils.

The titanium content in maize roots was highest in plants from treatments 2 and 3. In

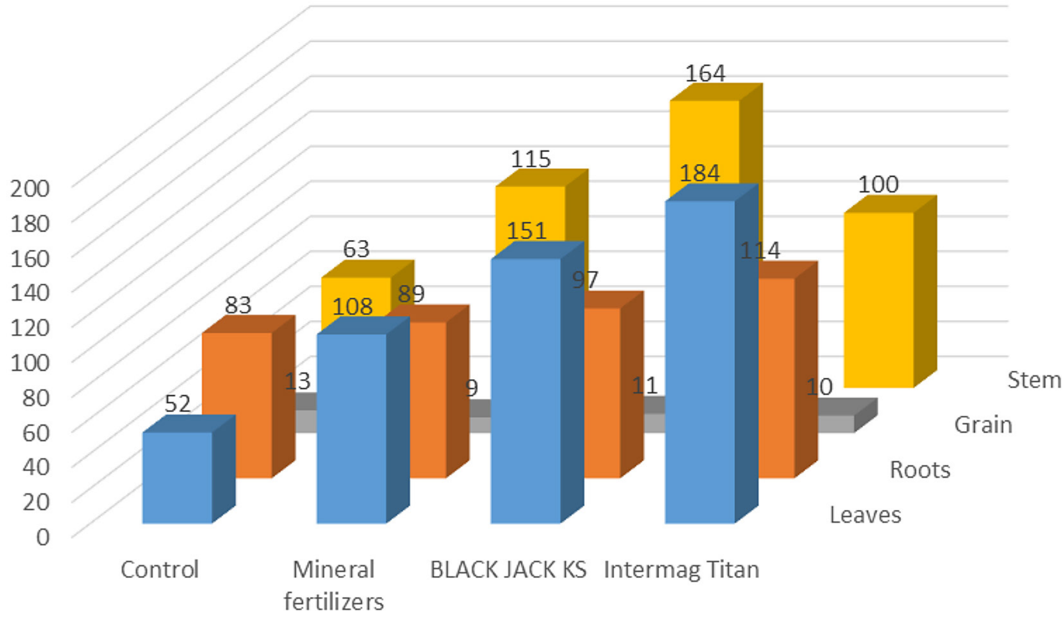

Figure 1. Phosphorus content in different parts of maize plants, mg/100 g

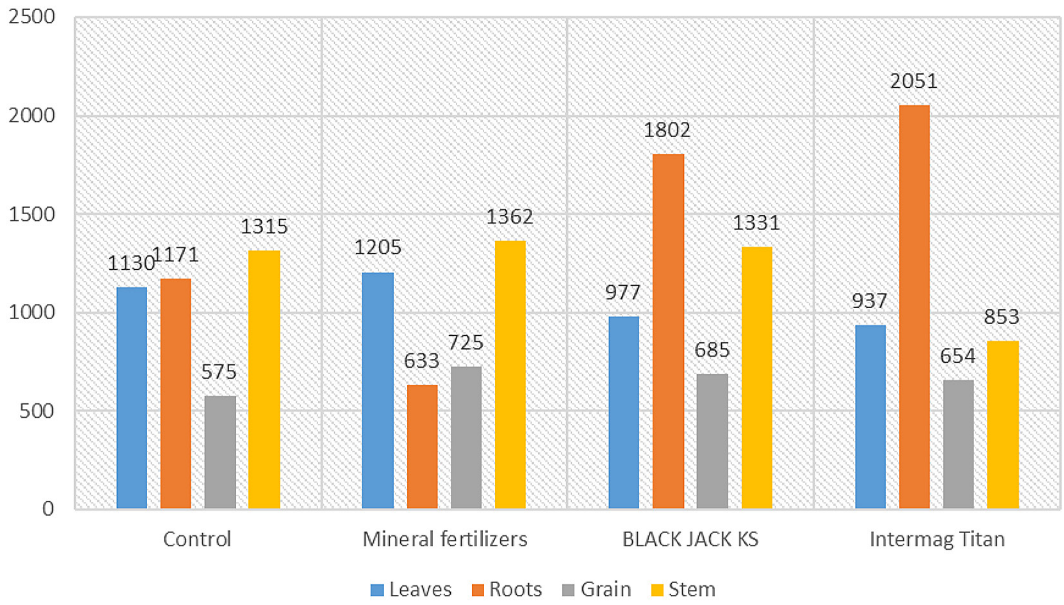

Figure 2. Potassium content in different parts of maize plants, mg/100 g

third place were plants treated with Intermag Titan. This can be explained by the insufficient amount of fertilizer applied; therefore, it is necessary to increase the number of applications from 3 to 5–6 times. The chromium content in maize roots was highest in treatment 3 plants (58 mg/100 g), which is almost 10 times higher compared to plants from other treatments, explained by its introduction together with the fertilizers. In the other treatments, chromium content remained at approximately the same level. The highest aluminium content in maize leaves (96 mg/100 g) was observed with the application of mineral fertilizers, whereas the highest calcium content was recorded in the treatment with Intermag Titan (1557 mg/100 g). Aluminium is not an essential element for plants, and its toxicity – particularly in acidic soils – can limit plant growth. Permissible levels of aluminium in food products are not strictly regulated

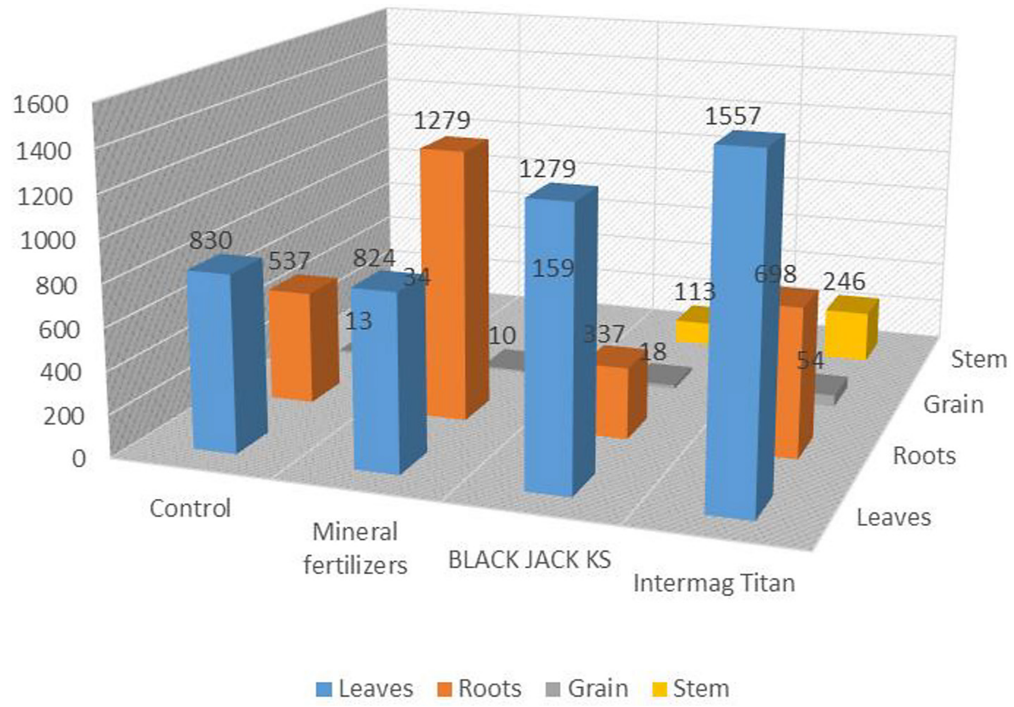

Figure 3. Calcium content in different parts of maize plants, mg/100 g

under the Codex Alimentarius; however, the European Food Safety Authority (EFSA) recommends a tolerable weekly intake (TWI) not exceeding 1 mg/kg of body weight. For animal feed, certain regulations (e.g., in Germany) stipulate that the aluminium content should not exceed 500–1000 mg/kg. Therefore, if the concentrations of chromium and aluminium detected in maize grain after fertilizer application exceed these thresholds, further evaluation is required to assess the potential risks to animal and human health, as well as environmental safety. The reasons for the accumulation of these elements may be related to the chemical composition of fertilizers or changes in the reaction of the soil environment.

Zinc content in roots was highest in control plants and in the mineral fertilizer treatment, amounting to 249 and 187 mg/100 g, respectively.

Regarding the microelement content in maize leaves, the highest aluminum content was recorded in the mineral fertilizer treatment (96 mg/100 g), and the lowest in the Black Jack KS treatment (37 mg/100 g); the other two treatments had almost identical values (44–45 mg/100 g). The highest calcium content was observed in the Intermag Titan treatment (1557 mg/100 g), while the lowest amounts were recorded in the mineral fertilizer treatment (824 mg/100 g) and the control (830 mg/100 g). However, these two treatments had the highest zinc contents – 1182 and 358 mg/100 g, which is 98% higher than in treatments 3 and 4.

Magnesium is a component of chlorophyll, acts as a cofactor for enzymes catalyzing phosphate group transfers, and is required for the activation of many enzymes of glycolysis and the Krebs cycle. It also maintains ribosome integrity. Similar to calcium, magnesium affects the incorporation of deoxyribonucleotides into the DNA molecule (Kots et al., 2005). It was found that the magnesium content in maize stems was highest in the control treatment – 48 mg/100 g, while in the stems of plants treated with Intermag Titan it was absent (Figure 4). Certain micronutrients contained in Intermag Titan (such as zinc or manganese) may inhibit magnesium uptake due to competition for the same transport pathways within the plant. In addition, fertilizer application could alter the cation ratio in the soil solution, thereby reducing magnesium availability. The specific soil conditions of the Carpathian region may have promoted the retention of magnesium in an available form in the absence of fertilization, whereas the application of Intermag Titan may have decreased its mobility or reduced the plant's physiological need for its uptake.

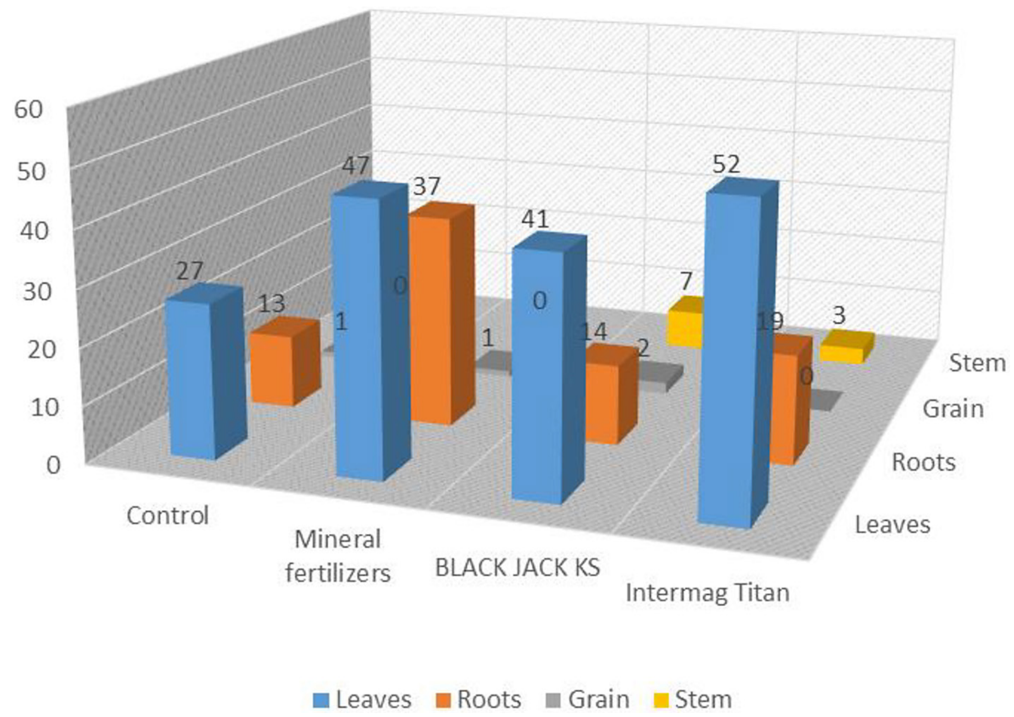

Figure 4. Magnesium content in different parts of maize plants, mg/100 g

Thus, the higher magnesium content observed in the control and its reduction or absence in the micronutrient treatment variants can be attributed to physiological competition among elements and the specific soil characteristics of the region.

Sulfur content in maize grain was almost the same across all treatments. The highest calcium content was observed in the Intermag Titan treatment (54 mg/100 g).

Zinc plays a key role in increasing the yield of green forage, as it is involved in numerous physiological processes in plants, such as chlorophyll formation, biomass accumulation, and stomatal regulation, which contribute to crop growth. Additionally, zinc can convert ammonia into nitrate in plants (Tamil Amutham et al., 2018). According to the results of their study on the concentration of microelements in maize plants, the highest iron content (122.75 mg/kg) was recorded under treatment F1, while the highest zinc content (34.62 mg/kg) was observed under treatment F2. In our studies, the zinc content in maize grain ranged from 3.46 mg/100 g in the variant treated with Intermag Titan to 5.87 mg/100 g in the variant treated with Black Jack KS. The zinc content in maize grain and stalks indicates that humates promote its accumulation to a greater extent than other experimental variants, which is not optimal for the safety of products obtained from such grain.

CONCLUSIONS

The highest phosphorus content was recorded in the treatment with the application of Intermag Titan, where its concentration in maize leaves was 184 mg/100 g and in roots – 114 mg/100 g, while in the treatment with Black Jack KS, the phosphorus content in maize stems was 164 mg/100 g. This indicates that titanium fertilizers promote the uptake of phosphorus and potassium by maize plants from the soil, whereas humates are a powerful source of potassium. It should also be noted that the application of mineral fertilizer at a rate of $N_{90}P_{90}K_{90}$ resulted in the highest potassium content, which amounted to 1205 mg/100 g in maize leaves, 1362 mg/100 g in stems, and 725 mg/100 g in grain.

It was found that the magnesium content in maize stems was the highest in the control treatment, reaching 48 mg/100 g. The highest aluminium content in maize leaves (96 mg/100 g) was observed with the application of mineral fertilizers, whereas the highest calcium content was recorded in the treatment with Intermag Titan (1557 mg/100 g). The lowest calcium levels were observed in the mineral fertilizer treatment (824 mg/100 g) and in the control (830 mg/100 g). However, these two treatments demonstrated the highest zinc content – 1182 and 358 mg/100 g, respectively.

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