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INFLUENCE OF MICROELEMENTAL FERTILIZERS AND SOWING TIME ON WINTER WHEAT DEVELOPMENT AND GRAIN QUALITY

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Future challenges in agriculture are not limited to increasing crop productivity. Farmers are striving to take sustainability principles into account, ensuring increased yields without additional harmful effects on the environment. One of the main ways we can ensure sustainable agricultural development is to use advanced methods and technologies designed to improve crop quality and increase yields.
The field experiment was carried out in 2023–2024 at the Experimental Station of Vytautas Magnus University Agriculture Academy. The two-factor experiment included four different sowing dates: September 7, September 14, September 21, and September 28 (Factor A), and additional fertilization with microelemental fertilizers (Factor B). Before the experiment was installed, the topsoil had a neutral reaction (pH–7.1), medium humus content (2.05%), high phosphorus content (241 mg kg^{-1}), and potassium content (186 mg kg^{-1}). Crops sown at the earliest sowing dates (September 7 and 14) and additionally fertilized exhibited the highest concentrations of chlorophyll (230.50–226.13 µmol m^{-2}), nitrogen (10.09–9.68%), and the highest NDGI index values (0.692–0.688). Wheat sown on September 7 and 14 and additional fertilization with microelemental fertilizers showed significantly better grain quality parameters: protein content (12.3–12.2 %), gluten content (25.0–23.6 %), sedimentation values (42.6–44.7 ml), and hectolitre weight (71.7–71.2 kg hl^{-1}).

Keywords: winter wheat, microelements, different sowing times, grain quality.

INTRODUCTION

Microelements are essential plant nutrients that play a vital role in the growth, development, and productivity of winter wheat. Their deficiency can not only reduce plant yield, but also impair grain quality and reduce resistance to adverse environmental conditions (Alloway, 2008). The uptake of microelements depends on soil properties, crop rotation, fertilization strategy, and meteorological conditions (Sobolewska et al., 2020). Microelements perform various physiological functions in wheat plants. Elements such as Fe, Cu, Mn, Cl, Zn, Ni, and Mo are involved in plant photosynthesis and various enzyme activities (Dimkpa, Bindraban, 2016). For example, zinc (Zn) is essential for enzyme activity, hormone synthesis, and protein metabolism, and its deficiency can cause slow plant growth and chlorosis. Manganese (Mn) is important for photosynthesis and carbohydrate metabolism, so its deficiency can lead to poorer energy use and affect grain formation. Copper (Cu) is involved in lignin synthesis and enzyme activity, and its deficiency can reduce plant resistance to disease and cause ear formation disorders. Boron (B) is vital for cell wall stability, generative organ development, and pollination, so its deficiency can reduce grain setting. Although potassium (K) is classified as a macroelement, it is often found in various microelement product mixtures because its importance is linked to osmotic regulation processes, plant resistance to drought and disease, so having enough of it in the soil can improve wheat yield and grain quality (Stepien, Wojtkowiak, 2016; Dimkpa, Bindraban, 2016; Sobolewska et al., 2020; Reynolds, Braun, 2022). Therefore, under modern farming conditions, to achieve an optimal winter wheat yield, it is necessary not only to ensure an adequate supply of macroelements but also to maintain a balance of microelements. Balanced microelement fertilization can not only increase yield, but also improve grain quality, increase protein and gluten content, which is particularly important for the food and feed industries (Sobolewska et al., 2020; Reynolds, Braun, 2022).

Maintaining microelement balance is one of the most critical factors in ensuring a stable and high-quality yield. A deficiency of one or more microelements can cause various growth disorders in winter wheat, which manifest themselves in visual symptoms, a slowdown in physiological processes, and reduced productivity (Rengel, 2015; Reynolds, Braun, 2022). However, the concentration of some microelements in tie soil can be very high and cause toxicity (Reynolds, Braun, 2022; Iancu et al., 2024). The balance of microelements is influenced by soil pH; for example, highly acidic soils may exhibit Al and Mn toxicity and Mo deficiency, while alkaline soils often exhibit B toxicity and Fe, Zn, and Mn deficiency (Stepien, Wojtkowiak, 2016; Iancu et al., 2024). Microelement toxicity occurs when the content of soluble nutrients in the soil exceeds the permissible limit. Aluminum (Al), boron (B), and manganese (Mn), which are important for wheat growth and development, are considered to have the most toxic effects (Reynolds, Braun, 2022). Manganese excess is most common in areas where soils are acidic and waterlogged or poorly drained. Signs of Mn toxicity include stunted growth, chlorosis, necrosis of leaf tips, and brown spots on mature leaves. Meanwhile, symptoms of boron toxicity include leaf necrosis at the tips of leaves, and high boron levels in the soil can cause severe root thinning (Dimkpa, Bindraban, 2016; Iancu et al., 2024).

The balance of microelements is an essential factor determining the growth, development, and productivity of winter wheat. Both a deficiency and an excess of microelements can cause severe physiological disorders that negatively affect plant health, disease resistance, and the final yield and quality of the crop. To optimize plant nutrition, it is necessary to regularly test soil and plant tissues and apply balanced fertilization tailored to specific growing conditions.

In modern agriculture, various products classified as plant growth stimulants are used in conjunction with plant protection products. This relatively new group of products is used to increase crop yields and improve quality, especially in unfavorable environmental conditions for plant growth and development. The purpose of biostimulants is to control and accelerate the vital processes of plants, increase their resistance to stress, and promote their development (roots and leaves). Biostimulants can be of various origins, obtained from multiple organic substances and their combinations – humic substances, seaweed extracts, amino acids, peptides, inorganic salts, etc. (Radzikowska-Kujawska et al., 2022; Vafa et al., 2024). These products are safe for the environment and contribute to sustainable, high-yield, low-cost crop production. Their use helps to reduce the amount of chemicals used in agriculture and plant protection (Popko, 2018). Humic substances (humic and fulvic acids) are natural components of soil organic matter formed by the decomposition of plant, animal, and microorganism residues (Du Jardin, 2015). Mixtures of amino acids and peptides are obtained by chemical and enzymatic hydrolysis of proteins from agricultural by-products, both from plant sources (plant residues) and animal waste (e.g., collagen, epithelial tissues) (Du Jardin, 2015; Vafa et al., 2024). Fresh seaweed has long been used as a source of organic matter and fertilizer in agriculture, but its biostimulating effect has only recently been documented. Studies have revealed that algae extracts contain various biostimulating compounds, such as various forms of carbohydrates, amino acids, small amounts of phytohormones, osmoprotectants, and proteins (Ali et al., 2021). It has been proven that seaweed biostimulants not only increase stress resistance, nutrient uptake, growth, and yield, but also help to reduce the dormancy period of seeds, improve the root system, flowering, fruit quality, and taste. This comprehensive effect results in higher crop productivity (Yakhin et al., 2017; Vafa et al., 2024).

Sowing time is one of the most essential agronomic factors affecting wheat development, winter survival, and yield. Sowing too early can lead to overly intensive vegetative growth before winter, increasing the sensitivity of plants to frost, while sowing too late can lead to insufficient tillering and weak plant development (Fazily, 2021). Therefore, optimizing the sowing time in combination with an appropriate microelement strategy can be a key factor in increasing the productivity of winter wheat. Under Lithuanian climatic conditions, plants must accumulate between 300 and 350 active temperature sums by the end of autumn vegetation. It takes about 50–60 days to accumulate these temperatures. The optimal time for sowing winter wheat is between September 10 and 25, but with climate change, these dates may change, and sowing may need to be brought forward to September 8–15 or slightly delayed. However, late sowing crops also occur for various agronomic reasons. Under favorable conditions, plants with 2–3 leaves can also overwinter. In spring, winter wheat vegetation resumes when the temperature reaches at least 3–5 °C. If winter wheat did not manage to tiller in the fall, it finishes tillering in the spring from the lateral shoots that formed in the fall. During the entire growing season, winter wheat accumulates a total of 2400–2700 °C of active temperatures (Šiuliauskas, 2015; Klepeckas et al., 2020; Khaeim et al., 2022). In their research on sowing time, Liu et al. (2021) confirm the common belief that sowing date is a key agronomic factor that improves the nutrient uptake of winter wheat and increases yield. Advancing or delaying sowing can compromise the full genetic yield potential of winter wheat. Grain yield decreases with both early and late sowing (Yin et al., 2018; Ma et al., 2018; Zhu et al., 2019; Gandjaeva, 2019). The optimal sowing time ensures rapid and uniform grain germination, which will allow for maximum winter wheat density and future yield. Sowing is often delayed due to various factors, which may depend on the course of technological processes and unfavorable weather conditions (Shah et al., 2020).

Research object – crop of winter wheat varietie \`Skagen\` sown on different times.

The purpose of the study – to determine and evaluate the influence of micronutrient fertilizers ant sowing time on winter wheat productivity.

RESEARCH METHODS

Experimental location and conditions. Field experiments were carried out at the Experimental Station of Vytautas Magnus University Agriculture Academy in Lithuania (54° 53' 3.26", 23° 50' 33.25") in vegetation season 2023–2024. The soil of the experimental field was *Cal(ca)ri-Epihypogleyic Luvisol* (WRB, 2022). Soil tests were performed before the experiment: pH_{KCl} of the topsoil was 7.1, high in available phosphorus P_2O_5 – 241 mg kg^{-1}, available K_2O – 186 mg kg^{-1}, and the humus content in the soil surface layer was 2.05%.

Experimental design. A two-factor experiment investigated sowing time and foliar spraying with microelemental fertilizers on winter wheat productivity.

Factor A – sowing date (7, 14, 21, 28 September);

Factor B – additional fertilization with microelemental fertilizers:

1. No additional fertilization.
2. Additional fertilization through the leaves.

The experiment was performed in six replications.

Used for additional fertilization: at the beginning of wheat tillering (BBCH 31–35) N 30 g l^{-1}, CaO 115 g l^{-1}, MgO 25 g l^{-1}, S 7 g l^{-1}, B 55 g l^{-1}, Cu 20 g l^{-1}, Mn 160 g l^{-1}, Mo 2 g l^{-1} (rate – 1.0 l ha^{-1}) + ascophyllum nodosum 150 g l^{-1}, alginic acid 24 g l^{-1}, free amino acids 100 g l^{-1}, fulvic acids 58 g l^{-1}, organic carbon 38 g l^{-1}, N-acyl L-cysteine, folic acid 0.1 g l^{-1} (rate – 1.0 l ha^{-1}) and at the end of wheat tillering (BBCH 37) Mn 100 g l^{-1}, S 67 g l^{-1}, amino acids 50 g l^{-1} (rate – 1.0 l ha^{-1}) + K 400 g l^{-1}, amino acids 40 g l-1 (rate – 1.0 l ha^{-1}).

Winter oilseed rape was used as the precrop. The bruto plot area was 40 (4x10) m^2 and the neto – 20 (2x10) m^2. The winter wheat variety 'Skagen' was cultivated in the experiment.

Background fertilization of winter wheat: ammonium nitrate (N51+N51) was applied in the spring after the regrowth of winter wheat (BBCH 20–26) and at the end of the winter wheat tillering stage (BBCH 27–30). Winter wheat was additionally fertilized through the leaves with urea (N10) during the stem elongation stage (BBCH 31–33). Plant protection measures were applied to prevent suppression of plant growth due to outbreaks of weeds, pests, and diseases.

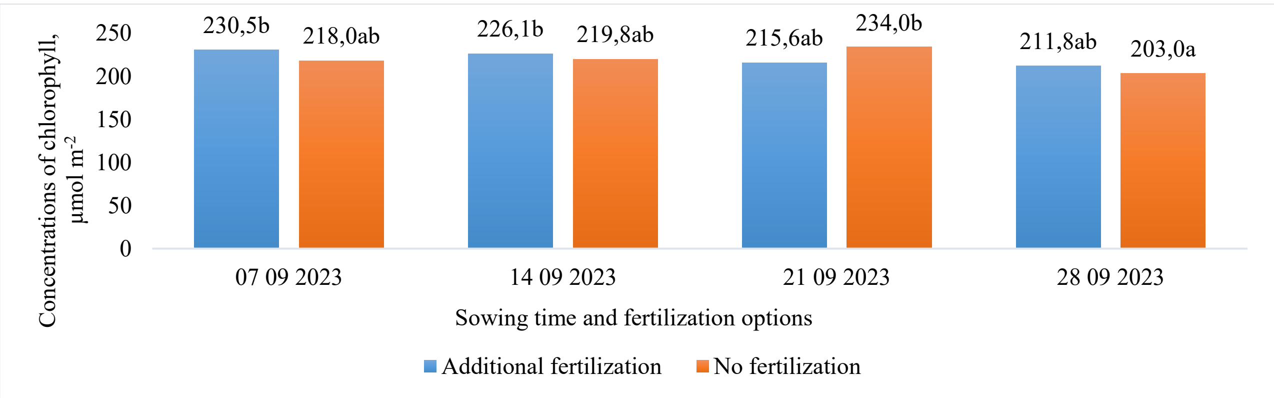
Experimental and analytical methods. Soil pH_{KCl} was measured by extraction with 1N KCl using the potentiometric method (LST EN ISO 10390:2021), organic carbon (C) – by the Tyurin method (LST EN 13037:2012), available phosphorus (P_2O_5) and potassium (K_2O) were determined according to the Egner-Riehm-Domingo (A-L) method (LST EN ISO 6878:2004; LST EN ISO 9964:3:1998), humus (%) was calculated by multiplying the carbon content by a factor of 1.724. The protein content was determined by the Kjeldahl method (LST EN ISO 20483), and wet gluten content by a GLUTOMATIC system (Perten) (according to LST EN ISO 21415-2; LST EN ISO 21415-4). Sedimentation values are determined in accordance with LST EN ISO 5529:2010/P:2012 Wheat. Determination of sedimentation index. Zeleny method (LST ISO 5529:2007), hectoliter mass – LST EN ISO7971–3:2019 (ISO 7971–3:2019). The normalized difference greenness index (NDGI) and nitrogen content in leaves were determined using the PlantPen model N 110 device, and chlorophyll concentration was determined using the Apogee MC-100 chlorophyll concentration meter.

Statistical analysis. The statistical reliability of the data was assessed by two-factor analysis of variance (ANOVA), using the software package SELEKCIJA. The statistical reliability of the data was evaluated by the lowest absolute limit of a significant difference R_{05} (data reliability: significant differences ($p<0.05$) between the means are indicated by different lowercase letters of the alphabet) (Raudonius, 2017).

RESEARCH RESULTS AND DISCUSSION

Plant photosynthesis is a crucial part of the carbon cycle, through which plants obtain carbon dioxide from the atmosphere. Maturing wheat mainly performs photosynthesis in its leaves and stems, which is the primary source of assimilation for cereals during grain filling (Saquee et al., 2023). When optimizing fertilization strategies, foliar application of various micro- and macroelements has a positive effect on plant physiological parameters and crop yield. Foliar fertilization of wheat is essential for increasing assimilation, plant growth, mass, quality, and yield (Bărdaş et al., 2023; Roşculete et al., 2023).

After analysis following the second additional fertilization with microelemental fertilizers during the flag leaf formation stage (BBCH 37), the highest chlorophyll concentration was found in unfertilized plants sown on September 21 – 234.0 µmol m^{-2} (Fig. 1). The chlorophyll concentration in the leaves of wheat sown at other sowing dates did not change significantly 10 days after the second additional fertilization. Still, it remained higher in the fields where the wheat was additionally fertilized.

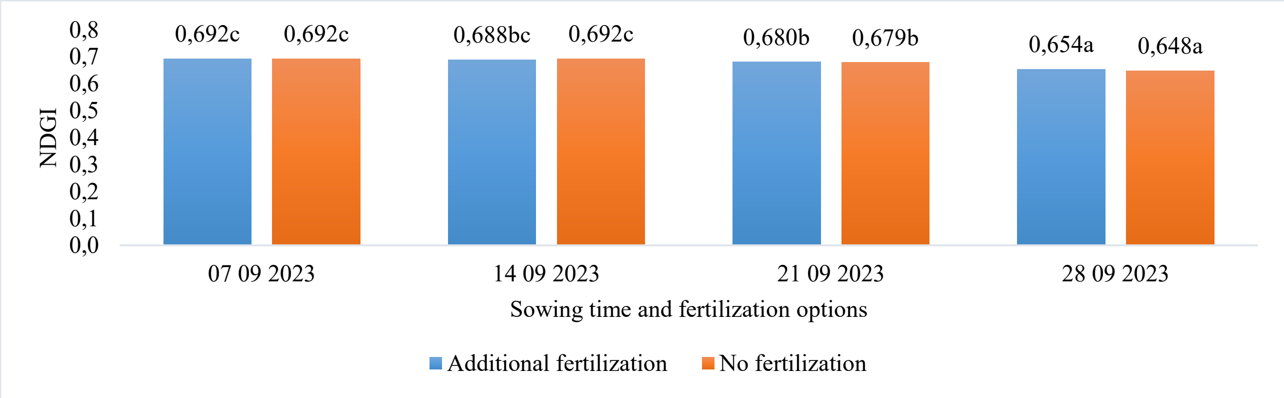


Note: differences between means marked with different letters (a, b, c...) are significant ($P<0.05$)

Figure 1. Chlorophyll concentration in winter wheat (BBCH 37) after the second additional fertilization

The NDGI index is defined as a normalized difference greenness index. This index reflects the dynamics of vegetation change. By analyzing the results obtained from NDGI, it is possible to more accurately assess momentary changes in vegetation condition (Nedkov, 2017; Yang et al., 2019). The ears and flag leaves absorb the most light, while the lower leaves absorb the least. Therefore, it is essential to optimize plant density so that the total light retention of the whole plant (canopy) increases and light energy is absorbed and used more efficiently (Gao et al., 2021).

The highest NDGI values were recorded in winter wheat sown on September 7 (both fertilized and unfertilized) and in winter wheat sown on September 14 and unfertilized – 0.692 (Fig. 2). The lowest NDGI value remained in the fields of the latest sown winter wheat (September 28). Still, the NDGI values were higher compared to the results determined before the second additional fertilization.

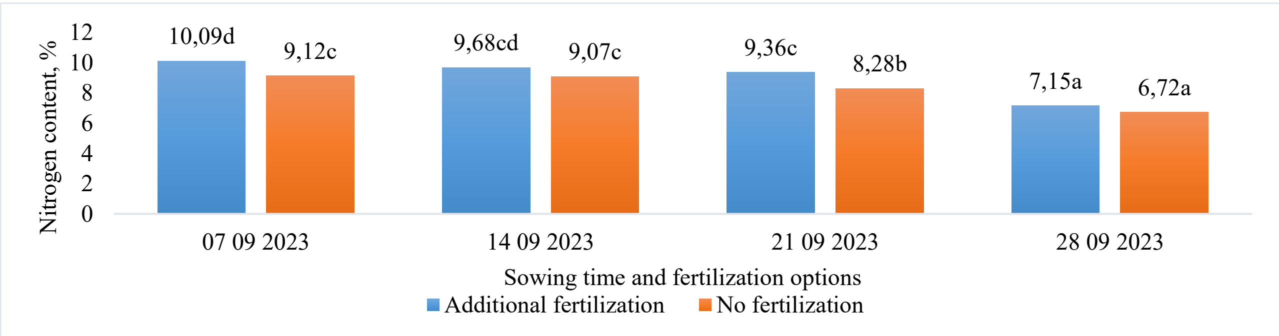


Note: differences between means marked with different letters (a, b, c...) are significant (P<0.05)

Figure 2. NDGI in winter wheat (BBCH 37) after the second additional fertilization

The amount of nitrogen in a plant is closely related to the intensity of photosynthesis and the overall yield potential. Nitrogen is an essential component of chlorophyll, which actively participates in the process of photosynthesis; therefore, its deficiency significantly reduces the efficiency of photosynthesis and plant productivity. The concentration of nitrogen in plants can vary considerably depending on the intensity of fertilization, soil properties such as organic matter content, pH, soil moisture, and aeration conditions, and meteorological factors such as temperature and precipitation (Taiz et al., 2015).

After the second additional fertilization with microelemental fertilizers, the analysis showed that the nitrogen content increased significantly in both fertilized and unfertilized wheat leaves (Fig. 3). A tendency was observed that, with delayed sowing, the nitrogen content in winter wheat leaves tended to decrease at the end of tillering and the beginning of flag leaf formation. The second additional fertilization with microelemental fertilizers helped to maintain a higher nitrogen content, especially in plants sown earlier. The highest nitrogen content (10.09%) was recorded on September 7 in additionally fertilized wheat, and the lowest on September 28 in unfertilized wheat (6.72%). This shows that additional fertilization with microelemental fertilizers at the beginning of flag leaf formation and early sowing was the most effective combination for maintaining nitrogen content in plants.

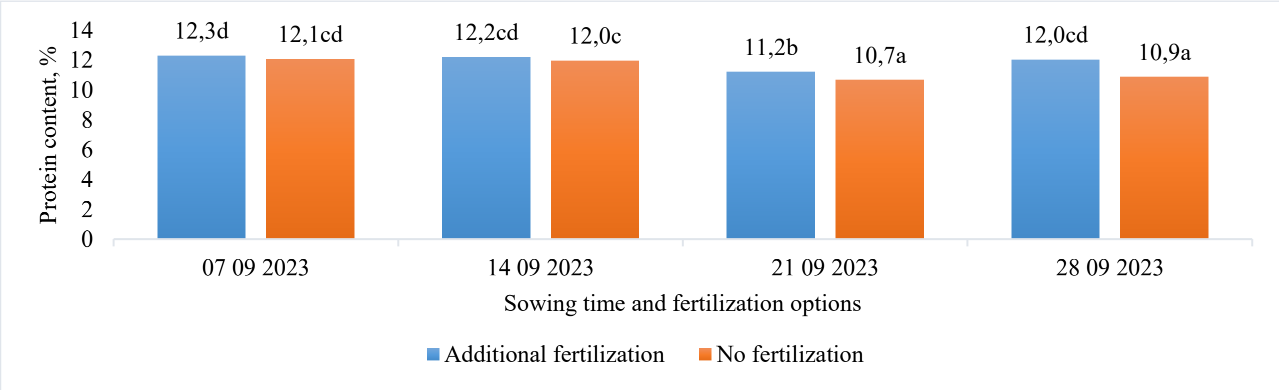


Note: differences between means marked with different letters (a, b, c...) are significant (P<0.05)

Figure 3. Nitrogen content in winter wheat (BBCH 37) after the second additional fertilization

The protein content of wheat grains is one of the most important quality indicators determining their nutritional value and technological properties. The protein content in wheat grains and flour usually ranges from 7% to 22%, but is most often 10–15% (Cato, 2020; Wieser et al., 2023).

The highest protein content (12.3%) was found in the earliest sown wheat grains (September 7), which were additionally fertilized with microelements. The lowest protein content (10.7–10.9%) was found in the latest sown wheat (September 21 and September 28), which was not sprayed with microelemental fertilizers. This shows that late sowing during the period under review was not conducive to higher protein content. It was observed that the use of microelemental fertilizers significantly increased the protein content in late-sown crops: fertilization increased the protein content by 4.5% in wheat sown on September 21 and by 4.4% in wheat sown on September 28. Early sowing combined with the use of microelemental fertilizers was the most effective combination for achieving higher protein content in wheat grains. Late sowing resulted in a significantly lower protein content, but additional fertilization helped to compensate for this decrease.

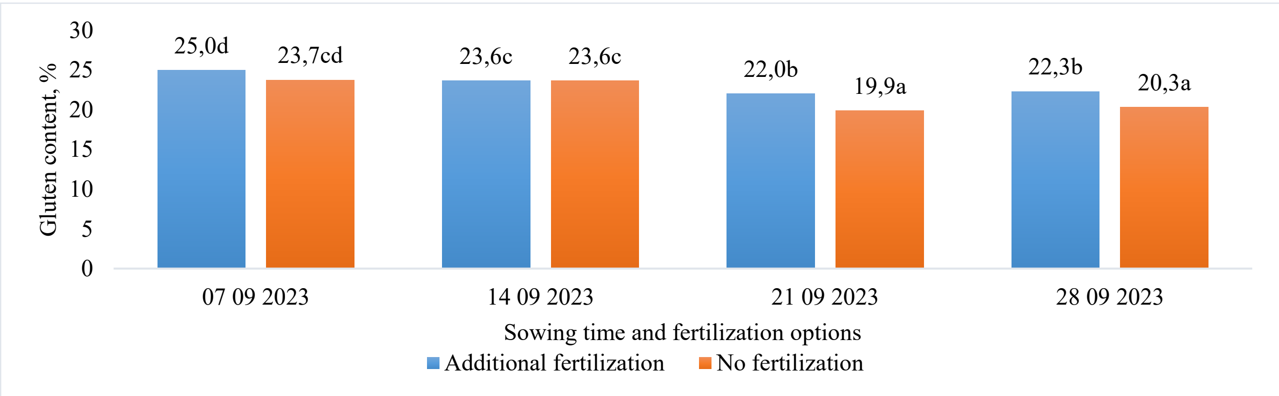


Note: differences between means marked with different letters (a, b, c...) are significant (P<0.05)

Figure 4. Protein content in winter wheat grains

Gluten content is closely related to bread-baking quality. Gluten is an essential component of bread quality and structure. Gluten can form a sticky and cohesive mass, films, and a three-dimensional network that are essential for baking properties, and its content increases along with the total protein content (Linina and Ruza, 2015).

Analysis of the study results (Fig. 5) shows that earlier sowing (September 7 and September 14) ensured a higher gluten content in wheat grains – 23.6–25.0%, while later sowing (September 21 and September 28) resulted in a lower gluten content – 19.9–22.3%. The significantly highest gluten content (25.0%) was found in the case of the earliest sowing (September 7), when the wheat was additionally fertilized with microelements. The lowest gluten content (19.9 and 20.3%) was found in the grains of wheat sown last (September 21 and September 28) and not fertilized with microelements.

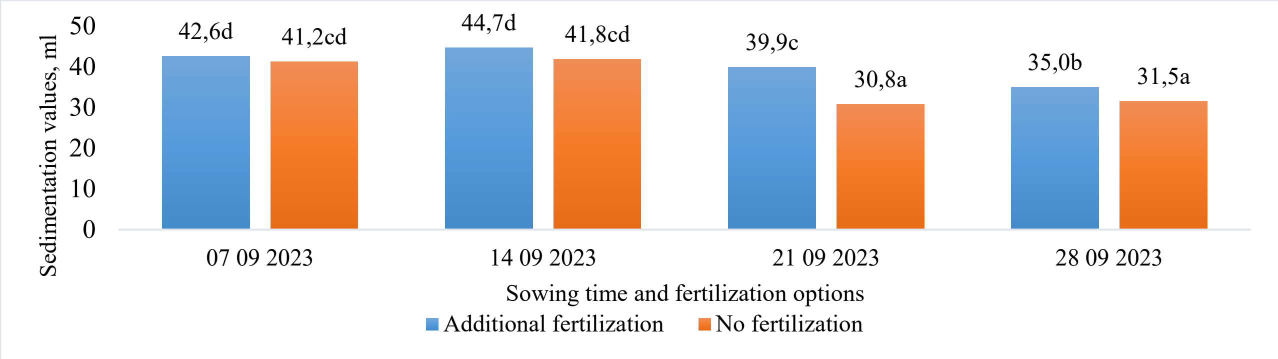


Note: differences between means marked with different letters (a, b, c...) are significant (P<0.05)

Figure 5. Gluten content in winter wheat grains

Sedimentation is an important indicator used to assess the quality of wheat and other cereal crops, especially their suitability for baking. This indicator determines the ability of flour to form a gluten network, which is essential for the elasticity and structure of bread dough. The sedimentation index characterizes the baking properties of grains. The higher the index, the better the structural and mechanical properties of the dough. The sedimentation index is highly dependent on the protein content in grains (Sasani et al., 2020; Kibkalo, 2022).

Sowing time and microelemental fertilization influenced the sedimentation index in wheat grains (Fig. 6). Earlier sowing (September 7 and September 14) resulted in higher sedimentation index values, ranging from 41.2 ml to 44.7 ml, while later sowing (September 21 and September 28) was associated with a lower sedimentation index, ranging from 30.8 ml to 39.9 ml. The highest sedimentation index (44.7 ml) was observed in the case of optimal sowing (September 14), when wheat was additionally fertilized with microelements. The significantly lowest sedimentation index (30.8 and 31.5 ml) was found in the latest sown wheat (September 21 and September 28), which was not additionally fertilized with microelements. It was observed that the use of microelemental fertilizers increased the sedimentation index values in wheat grains sown at all sowing dates.

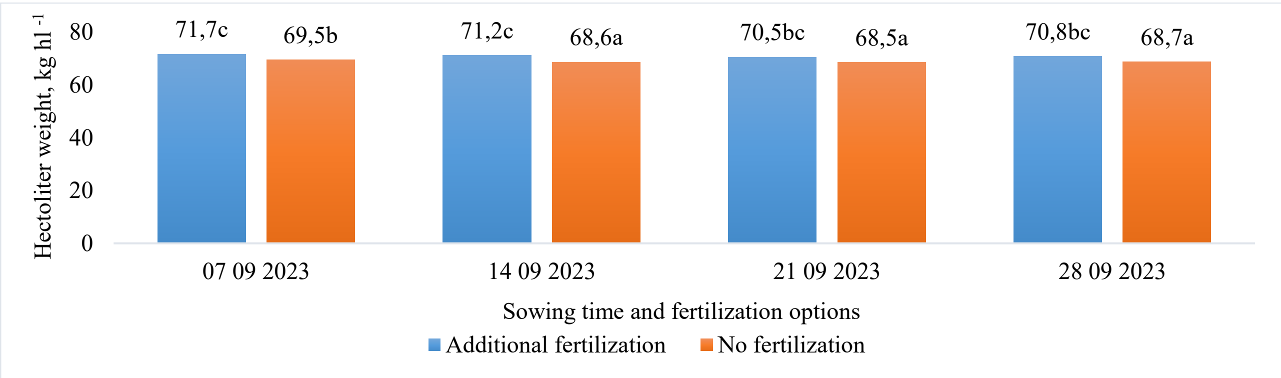


Note: differences between means marked with different letters (a, b, c...) are significant (P<0.05)

Figure 6. Sedimentation index values in winter wheat grains

Hectoliter weight is a genetically determined trait that varies greatly depending on environmental factors such as agroecological conditions and production technology. Hectoliter weight indicates the weight of one hectoliter of wheat, expressed in kilograms, and is recognized as a measure of wheat quality due to its simplicity and quick determination. It can also be used as a reference value for assessing milling quality and ranges from 60 to 84 kg hl^{-1} (Madic et al., 2024).

The highest hectoliter weight (71.7 kg hl^{-1}) was found in the case of early sowing (September 7), when the wheat was additionally fertilized with microelements (Fig. 7). The lowest hectoliter weight (68.5 and 68.7 kg hl^{-1}) was found in winter wheat sown on September 14, September 21, and September 28 and not fertilized with additional microelements. This shows that early sowing combined with additional microelemental fertilization was more favorable for the formation of a higher hectoliter weight.



Note: differences between means marked with different letters (a, b, c...) are significant (P<0.05)

Figure 7. Hectoliter weight of winter wheat

It was found that the use of microelemental fertilizers significantly increased the hectoliter weight regardless of the sowing time. Thus, it can be assumed that early sowing combined with microelemental fertilization was the most effective combination for achieving a higher hectoliter weight of wheat grains.

CONCLUSIONS

Microelemental fertilizers had a positive effect on chlorophyll concentration and nitrogen content in plant leaves. During the flag leaf formation stage, the highest chlorophyll concentrations (230.5 and 226.1 µmol m^{-2}) and nitrogen content in leaves (10.09 and 9.68%) were found in winter wheat sown on September 7 and 14 and additionally fertilized. NDGI was higher in crops sown on September 7 and 14 (0.692 and 0.688), while the values of this indicator in the latest sowing (September 28) wheat decreased significantly, and additional fertilization with microelements had no significant effect.

Additional fertilization with microelemental fertilizers improved the quality indicators of winter wheat grains. The grains of winter wheat sown on September 7 and 14 and additionally fertilized had significantly higher protein (12.3 and 12.2%), gluten (25.0 and 23.6%), sedimentation values (42.6 and 44.7 ml), and hectoliter weight (71.7 and 71.2 kg hl^{-1}). Significantly lower protein (10.7 and 10.9%), gluten (19.9 and 20.3%), and sedimentation values (30.8 and 31.5 ml) were found in wheat grains sown on September 21 and 28 and not fertilized additionally.

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