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PHOTOSYNTHETIC ACTIVITY OF SPRING WHEAT ON CHERNOZEM SOIL UNDER DIVERSE MINERAL NUTRITION IN NORTHERN KAZAKHSTAN

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SUMMARY

The pertinent study assessed the different photosynthetic activity parameters in spring soft wheat (*Triticum aestivum* L.) genotypes based on diverse mineral nutrition levels. The dynamics of leaf area growth, photosynthetic potential, and net crop productivity at various developmental stages reached analysis. The determined average correlation between yield and flag leaf area for three research backgrounds showed that not all wheat genotypes responded equally to the mineral fertilizer due to their varied biological characteristics and genetic backgrounds. It was also evident that enhancement in leaf area and photosynthetic parameters appeared in wheat genotypes when applied with complete fertilizer doses. For instance, the following rates emerged for the maximum flag leaf area (12 300 m^2/ha), the total leaf area (17 700 m^2/ha), photosynthetic potential (0.960 million m^2/day), and the net photosynthesis productivity (6.7 g/m^2 per day), with the average grain yield on this background was 3.3 t/ha. The increase in the number of nodal roots of spring soft wheat genotypes mainly responded to the different mineral nutrition levels. In the context of a 0.5 calculated dose of mineral fertilizer, seven out of nine wheat lines had 22% more nodal roots, and the utmost calculated dose of mineral fertilizer was 24% more than the control treatment (unfertilized background), which was crucial for increasing the productivity considerably.

Keywords: Spring soft wheat (*Triticum aestivum* L.), mineral fertilizers, photosynthesis, leaf area, photosynthetic potential and productivity, grain yield, nodal roots

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Key findings: The results showed that based on the levels of mineral nutrition of spring wheat genotypes on the leaves’ photosynthetic activity, root system development, and productivity, the genotypes differed in their reaction to the mineral fertilizers due to their varied biological characteristics and genetic makeup. The results also revealed that the considerable enhancement of leaf area and photosynthetic parameters in spring wheat genotypes surfaced when applied with the highest dose of mineral fertilizers.

INTRODUCTION

Spring soft wheat (*Triticum aestivum* L.) is a mainly cultivated crop in the Northern regions of Kazakhstan with a high economic value in the global market. The sharply continental climate of this zone does not always meet production requirements due to variability in crop yields year to year. Spring wheat with high and sustainable yield is a priority for the producers, which can be successful through developing and adapting innovative cropping technologies (Kulinich and Berdagulova, 2015; Kenenbaev and Bastaubaeva, 2016). Past studies confirmed that under the arid climate conditions of Northern Kazakhstan, the potential yield of spring wheat cultivars under moisture-favorable seasons can reach up to 3.0 t/ha; however, its average yield in this region is only 1.0–1.2 t/ha. Modern innovative cultivation practices and mineral fertilizer use are key factors contributing to a 30%–40% increase in crop grain yield. The time-consuming process of developing new high-yielding wheat cultivars through conventional plant breeding necessitates exploring novel approaches (Karpova, 2014; Sedlovsky *et al*., 2014; Tsyganova *et al*., 2019; Zotova *et al*., 2019; Baidyussen *et al*., 2023; Kushanova *et al*., 2023).

Mineral fertilizer application is one of the strategies for enhancing crop yield, as it accelerates the photosynthetic activity vital in the plant's crop formation. Photosynthetic activity depends on the biological characteristics of the plant, the phenological phases of crop development, crop growth, and environmental conditions. Activating the photosynthesis process enhanced plant productivity, contributing to the formation of 90% of the dry matter in crops. In turn, the photosynthetic activity depends on the intensity of development, the leaf area, and the duration of its operation. During the plant's vegetative period, forming the leaf surface to some extent also acquires influences from planting density. The leaf area in spring wheat reaches its maximum size during the heading phase. However, achieving the optimal leaf area is under sufficient water, nutrients, and favorable temperature conditions (Nichiporovich, 1959; Vasin *et al*., 2021). The photosynthetic activity of crops is directly proportional to the nutrient elements found in the soil. In a productive process, the leaf surface area and the net photosynthetic productivity are the most critical indicators. The size and duration of leaf surface operation, especially during the reproductive phase, considerably shape the grain productivity in crop plants (Absatarov, 1992).

A study of the influence of the humic preparation 'Humostim’ and mineral fertilizers on the productivity formation of spring soft wheat cultivar Tulaikovskaya-108 transpired in the forest-steppe zone conditions of the Middle Volga region (Bogomazov *et al*., 2023). The study revealed that mineral fertilizers enhanced the net photosynthetic productivity to 5.30 g/m² per day, spike graininess by 36%, and the grain yield of spring wheat by 1.01 t ha^{-1}. The combined application of Gumostim and mineral fertilizers also increased the net photosynthetic productivity (5.47 g/m² per day), spike graininess (83%), grain weight per plant (45.8%), and the grain yield of spring wheat (1.55 t ha^{-1}).

A past study investigated the impact of nitrogen fertilizers on the grain yield and quality of winter wheat cultivar ‘Grom’ on meadow-chestnut soil (Teymurov *et al*., 2023). It found that nitrogen fertilization improved the indicators of seed quality, especially the baking quality. The results further showed that seed vigor was 99%, germination was 100%, 1000-grain weight was 34.7 g, and protein and gluten content was 14.8% and 27.4%, respectively, which were 4.0%, 4.0%, 3.9%, 1.3%, and 6.1% higher than the control variant (no fertilizer), respectively. The nitrogen fertilizers (N_{30},N_{60},N_{90}) in combination with P90 increased the winter wheat yield by 6.25 to 7.90 t ha^{-1}. In the arid conditions of Northern Kazakhstan, the previous research showed the effectiveness of top-dressing spring wheat crops with urea-ammonium nitrate solution CAN-32. The rise in grain yield of the intensive spring wheat was justified by the growth of the assimilative surface area of the crop (Nokusheva *et al*., 2023).

The studies demonstrated that the increase in grain yield of intensive spring wheat cultivars succeeded by expanding the crop's assimilation surface area (Stasik, 2005). The primary factor influencing crop formation is the flag leaf area, especially during the grain-filling period, while stem reserves also play a supplementary and backup role. The redistribution of protein in the grain occurs through the utilization of two sources of nitrogen compounds, i.e., the reutilization of nitrogen accumulated in vegetative organs (mainly in leaves and stems) until flowering and the uptake of nitrogen from the soil during grain formation and ripening stages (Barraclough *et al*., 2014; Yusov *et al*., 2015).

Long-term field experiments revealed enhancements in the spring wheat grain yield when applied with increased doses of phosphorus fertilizers (Pashtetsky *et al*., 2020; Sultanov *et al*., 2021). Compared with the control variant, the treatments of 50, 100, and 200 kg/ha of P_2O_5 improved the wheat grain yield by 60%, 85%, and 138%, respectively. As the phosphorus fertilizer dose increases, a decline in the degree of wheat infection with root rot and its spores also occurs. In addition, an upsurge in the soil's organic carbon and total nitrogen content was evident. The optimal doses of phosphorus fertilization improved the grain quality (0.7–0.9 times) and notably enhanced the protein content in wheat grains (10.1% to 12.7%) and wheat grain yield (1.5 times) (Cardas and Ibrahim, 2023).

In recent years, several researchers have obtained data from studies indicating that agrochemical-treated efficient varieties of crops possess a distinctive feature. Past studies suggested that these varieties could absorb more mineral nutrients from the soil and fertilizers and synthesize more organic matter per unit of absorbed element than other varieties (Rempelos *et al*., 2020). Previous studies reported that one of the tasks in developing agricultural technologies is substantiating the optimal fertilizer application rates, considering the genetic peculiarities of the nutrition of a specific variety (Volynkina, 2021). The treatment of mineral fertilizers in spring wheat cultivation boosts its productivity. Moreover, different varieties exhibited varying responses to the action of mineral fertilizers (Nikiforova and Zakharov, 2020). The presented research examined the influence of the diverse levels of mineral nutrition on the photosynthetic activity and grain yield of mid-ripening spring soft wheat genotypes on the chernozem soils in Northern Kazakhstan.

MATERIALS AND METHODS

Breeding material and procedure

The latest study utilized the spring soft wheat cultivar (Erythrospermum 738) and eight other wheat lines (Lutescens 814 sp2/09, Lutescens 1148 sp2/09, Lutescens 857 sp2/05, Lutescens 1206 sp2/19, Lutescens 1143 sp2/09, Lutescens783 sp2/07, Lutescens821 sp2/08, and Lutescens 715 sp2/04), developed at the Kazakh Research Institute of Agriculture and Plant Growing, Almalybak, Kazakhstan. A regionally adapted cultivar of spring soft wheat (‘Omskaya 36’) served as the standard, making the total studied spring wheat genotypes ten. All the studied wheat received three diverse nutrient regimes, i.e., without fertilizers, 0.5 of the calculated dose ($N_{31}P_{33}$), and the highest calculated dose ($N_{62}P_{66}$), which amounted to $N_{65}P_{69}$ in 2021 and $N_{58}P_{62}$ in 2022, with an average of $N_{62}P_{66}$. The fertilizers used included ammonium nitrate and double-granulated superphosphate.

For the said region, the research followed conventional agricultural practices. The preceding crop was a fallow field. Sowing at the optimal timing transpired around May

22-23, with a seeding rate of 3.0 million seeds per hectare. The total plot area was 25 sq m, with four replications. The experimental soil was a typical carbonate black soil, moderately humus, with a shallow heavy clay loam texture. The soil content has the following: the pH (7.1), organic matter content (4.0%), moderate nitrate nitrogen content (9.3 mg/kg), low mobile phosphorus content (4.0 mg/kg), and high potassium content (360 mg/kg). Field and laboratory research used the methodology of the State Cultivar Testing for Agricultural Crops (1985).

Meteorological conditions

During the crop season study, the meteorological conditions varied for precipitation and temperature patterns, affecting the duration of interphase periods, the overall growing season, and the spring wheat formation of key grain yield components. In 2021, the hydrothermal coefficient for the entire growing season was, on average, 0.4, nearly half of the long-term average data, where the hydrothermal coefficient equals 0.9. In 2021, the May month was exceptionally dry, with a hydrothermal coefficient of 0.2, while in 2022, the long-term average data reached 0.9. The favorable conditions positively affected the spring wheat seed germination and uniform emergence of seedlings. June had a drought period, especially in the first and second 10 days, with a hydrothermal coefficient of 0.5, which was 0.9 units lower in 2021 than in 2022. The high temperature and moisture levels in June 2022 (hydrothermal coefficient = 1.4, compared to the long-term average of 0.8) positively influenced the interphase period (tillering – heading). The hydrothermal coefficient for 2021 was 0.6, 0.4–0.5 units lower than in 2022 and the long-term average data. In the dry season 2021, characterized by a May-June drought and uneven precipitation distribution throughout the growing season, the hydrothermal coefficient ranged from 0.5 to 0.6 (June-July). In August 2021–2022, the hydrothermal coefficient was only 0.12–0.4, lower by 0.58–0.3 units than the long-term data average (Figure 1).

Data recorded and statistical analysis

Leaf area and net photosynthetic productivity determination was according to Nichiporovich (1959)., Calculating the beneficial action coefficient of photosynthetically active radiation to assess the performance of the assimilation apparatus followed the methodology of Gulyaev (1963). Leaf surface measurements proceeded during the following phenophases, i.e., emergence, tillering, heading, flowering, milk ripeness, and wax ripeness (1969). The different observations and data collection progressed following the State

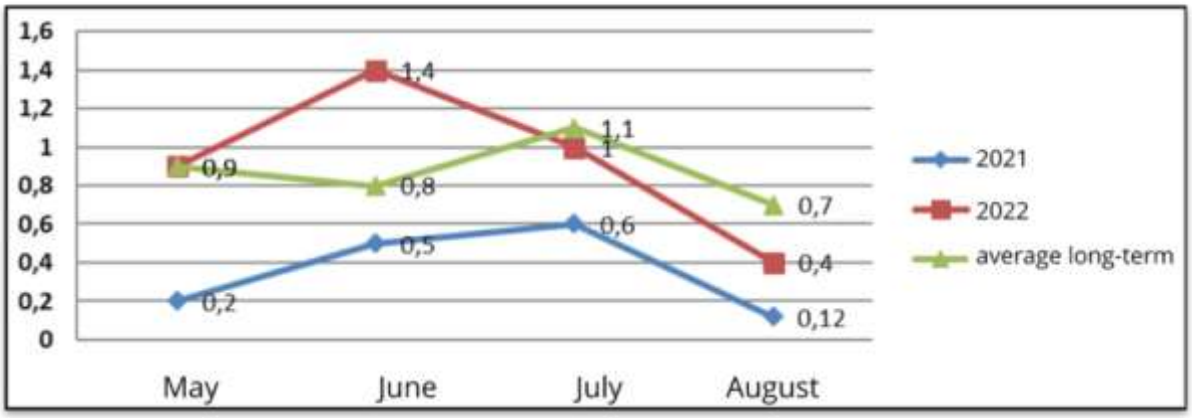

Figure 1. Hydrothermal coefficient – 2021–2022.

Cultivar Testing methodology (1985). Experimental data analysis used the AgStat program (http://www.sniish.ru/proposal_desc.php?id=8). Based on the analysis of variance (ANOVA), the least significant difference ($LSD_{0.05}$) test helped the comparison and separation of different calculated means, along with coefficients of variation (Cv) and correlations (r) following the methodology of Dospekhov (1985).

RESULTS AND DISCUSSION

The promising study engaged three diverse conditions of mineral fertilizer nutrition, i.e., control (without fertilization), 0.5 doses, and 100% of the calculated dose of mineral fertilizers, to examine the impact of these conditions on the productivity of spring soft wheat genotypes. The measurement included the area of the flag leaf and all other leaves. Determining the correlation relationship for each nutrient regime also ensued.

Under the control treatment (no fertilizer), the flag leaf area of the standard spring wheat cultivar Omskaya-36 was 8,500 m^2/ha. However, on average, the studied wheat lines had a higher flag leaf area, ranging from 1,200 to 3,100 m^2/ha, than the control variant. An exception was the wheat line Lutescens 821 sp2/08, which had a flag leaf area of 1,200 m^2/ha lower than the control and the genotype Lutescens1206 sp2/19, which was close to the control (8,700 m^2/ha). Line Lutescens 715 sp2/04 had the maximum flag leaf area, exceeding the control by 3,100 m^2/ha. In the control variant, the total leaf area was 12,400 m^2/ha, while the lines Lutescens 857 sp2/05, Lutescens 1143 sp2/09, Erythrospermum 738, Lutescens1148 sp2/09, Lutescens 814 sp2/09, and Lutescens715 sp2/04 had significantly higher leaf areas, measuring 13,300, 14,700, 14,700, 15,500, 15,600, and 16,700 m^2/ha, respectively.

The spring wheat line Lutescens783 sp2/07 had a significantly lower leaf area (11,500 m^2/ha), and the lines Lutescens 821 sp2/08 and Lutescens 1206 sp2/19 showed a nonsignificant difference from the control, with areas ranging from 11,500 to 12,200 m^2/ha, respectively. For the standard spring wheat cultivar Omskaya-36, the grain yield was 1.8 t/ha. The lines Lutescens 821 sp2/08, Lutescens 1143 sp2/09, Lutescens 814 sp2/09, Lutescens1148 sp2/09, and Lutescens715 sp2/04 had significantly higher grain yields, measuring 2.0, 2.1, 2.4, 2.5, and 3.0 t/ha, respectively, with an increase ranging from 11.1% to 66.7%. The spring wheat line Lutescens 715 sp2/04 achieved the highest grain yield (3.0 t/ha), exceeding the control by 66.7%. A moderate association was visible between the grain yield and flag leaf area (r = 0.57), and a considerable correlation was evident with the total leaf area (r = 0.87) (Figure 2). The development of the leaf surface area in the tillering phase on poor soils (Perm

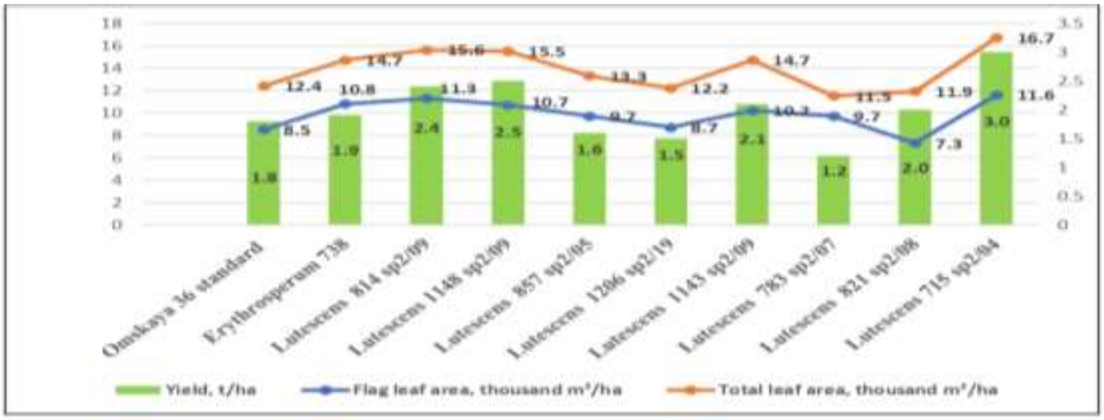

Figure 2. Leaf area and grain yield of mid-ripening spring soft wheat lines, no fertilizer regime (average for 2021–2022).

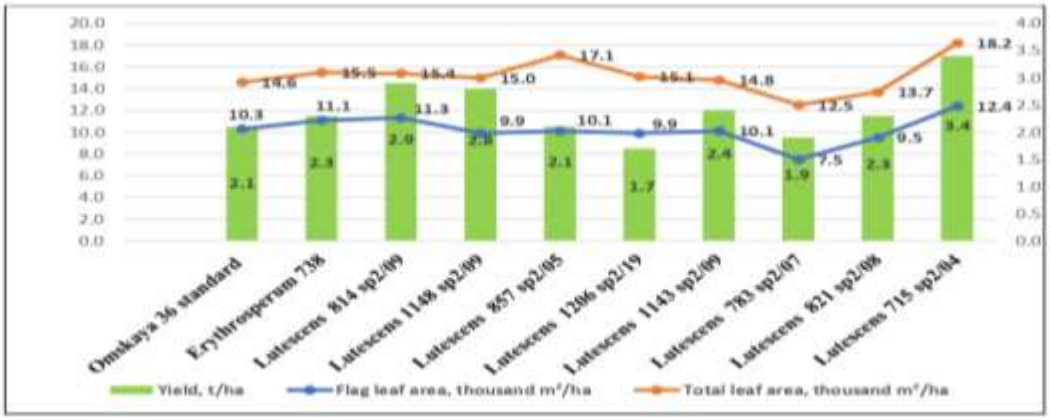

Figure 3. Leaf area and grain yield of mid-ripening spring soft wheat lines, half-calculated fertilizer dose regime (average for 2021–2022).

Krai, Russia) with a limited water and nutrient regime was 7,500–8,900 m2/ha. Maximizing the growth of the leaf area until the end of the growing season is vital to increase the yield (Nichiporovich, 1970; Nevodina et al., 2013).

With a half dose of the calculated dose of mineral fertilizers, the spring wheat standard cultivar Omskaya-36 had a leaf area of 10,300 m^2/ha, and lines Erythrospermum 738, Lutescens 814 sp2/09, and Lutescens 715 sp2/04 had their leaf area significantly higher at 11,100, 11,300, and 12,400 m^2/ha, respectively. For the spring wheat lines Lutescens783 sp2/07, Lutescens 821 sp2/08, Lutescens 1148 sp2/09, and Lutescens1206 sp2/08, the leaf area was lower than the control by 400–2,800 m^2/ha. However, for lines Lutescens 857 sp2/05 and Lutescens 1143 sp2/09, the leaf area was at the level of the control variant (10,100 m^2/ha). In the control treatment, the total leaf area was 14,600 m^2/ha, and for the wheat lines Lutescens 814 sp2/09, Erythrospermum 738, Lutescens 857 sp2/05, and Lutescens 715 sp2/04, the total leaf area was significantly higher at 15,400, 15,500, 17,100, and 18,200 m^2/ha, respectively. Line Lutescens 783 sp2/07 had a substantially lower score (2,100 m^2/ha). The remaining spring wheat lines showed a nonsignificant difference in leaf area from the standard cultivar. The grain yield for the spring wheat standard cultivar Omskaya-36 was 2.1 t/ha. For the studied lines, Erythrospermum 738, Lutescens 821 sp2/08, Lutescens 1143 sp2/09, Lutescens 1148 sp2/09, Lutescens 814 sp2/09, and Lutescens 715 sp2/04, the grain yield was remarkably higher at 2.3, 2.3, 2.4, 2.9, and 3.4 t/ha, respectively, with an increase ranging from 9.5% to 61.9%. The spring wheat line Lutescens 715 sp2/04 provided the maximum grain yield (3.4 t/ha), surpassing the standard cultivar by 61.9%. A strong correlation (*r* = 0.70) appeared between the leaf area and grain yield, while the association with the total leaf area was weak (*r* = 0.56) for the studied spring wheat lines (Figure 3). Studies in the Ulyanovsk region, Russia, showed that with varied phosphorus concentrations, the leaf photosynthesis rate and leaf area decreased considerably, with the decrease in leaf area occurring faster than the decline in leaf photosynthesis (Nikitin, 2017).

With a maximum dose of recommended mineral fertilizers, the flag leaf area in spring wheat standard cultivar Omskaya-36 was 11,800 m^2/ha, while for the studied lines, it varied from 12,800 (Lutescens 1148 sp2/09) to 14,900 m^2/ha (Lutescens 715 sp2/04). Exceptions were the spring wheat lines Lutescens 783 sp2/07 and Erythrospermum 738, with a flag leaf area of 1,900–2,000 m^2/ha lower than the control variant. The values of the lines Lutescens 857 sp2/05 and Lutescens 1143 sp2/09 were close to the control at 11,400–11,500 m^2/ha. The spring wheat line Lutescens 715 sp2/04 emerged with the utmost flag leaf area (3,100 m^2/ha).

With a background of the utmost calculated dose of mineral fertilizers in the standard variant, the leaf area was 16,300 m^2/ha. The spring wheat lines Lutescens 1143 sp2/09, Lutescens 1206 sp2/19, Lutescens 857 sp2/05, Lutescens 814 sp2/09, Lutescens 1148 sp2/09, and Lutescens 715 sp2/04 had significantly higher values at 17,700, 18,300, 18,700, 19,000, 19,000, and 20,400 m^2/ha, respectively. Line Lutescens 738 sp2/07 was relatively lower at 14,200 m^2/ha, while the spring wheat lines Erythrospermum 738 and Lutescens 821 sp2/04 were at the standard level, ranging from 16,000 to 16,900 m^2/ha.

With the highest calculated dose of mineral fertilizers, the grain yield in the spring wheat standard cultivar Omskaya-36 was 2.3 t/ha. The grain yield for lines Lutescens 857 sp2/05 was 2.5 t/ha, while for Lutescens 1143 sp2/09 and Lutescens 821 sp2/08, it was 2.6 t/ha. The spring wheat line Erythrospermum 738 had a grain yield of 2.9 t/ha, Lutescens 814 sp2/09 had 3.1 t/ha, Lutescens 1148 sp2/09 had 3.2 t/ha, and Lutescens 715 sp2/04 had the utmost yield of 3.3 t/ha, establishing an increase of 8.7%–43.5% over the control treatment. The line Lutescens 715 sp2/04 achieved the maximum grain yield, exceeding the control by 43.5%.

However, the grain yield of this line had a nonsignificant difference from its baseline yield (3.4 t/ha), obtained under a 0.5-calculated dose of fertilizers. It indicates a weak responsiveness of this line to high levels of agricultural intensification under conditions of insufficient moisture and its homeostatic nature. Homeostasis is evident given that in drought conditions during 2021, the grain yield of the Lutescens 715 sp2/04 line, with minimal mineral nutrition, did not differ significantly, ranging between 0.90–0.95 t/ha. In other words, fertilization provided no increase in yield. In the humid conditions of 2022, under fertilized backgrounds, the increment amounted to 0.70–0.83 t/ha. Interestingly, the utmost calculated dose did not ensure a yield increase compared with the 0.5 calculated doses, indicating moderate responsiveness of the specified line to the level of mineral nutrition.

A weak correlation (r = 0.43) was apparent between the grain yield and the flag leaf area, and a moderate correlation surfaced with the total leaf area (r = 0.66) (Figure 4). The study in the Akmola region, Kazakhstan, also revealed that by applying mineral fertilizers, the increase in wheat yield to the control ranged from 0.1 to 0.3 t/ha (7.1%–19.8%) (Mukhanbet *et al*., 2016). Based on the studies carried out in Altai Territory, Russia, mineral fertilizers have established a

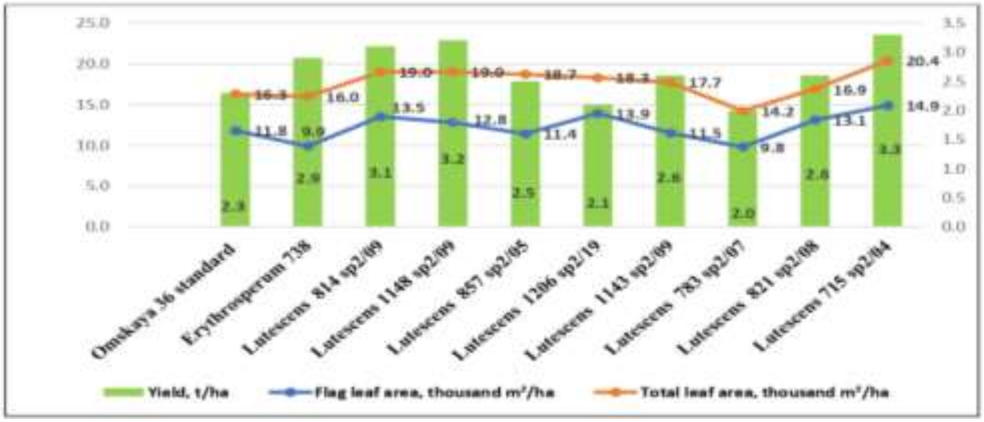

Figure 4. Leaf area and grain yield of intermediate-maturing spring wheat lines, fertilization background – maximum-calculated dose (average for 2021–2022).

significant positive correlation (*r* = 0.73) between the leaf area and wheat yield, which assured the effectiveness of mineral fertilizers in boosting the yield (Khizhnyakova and Chernetsova, 2014).

In the experimental plots, before sowing in the root zone of the soil (0–40 cm), the nitrate-nitrogen content was 9.3 mg/kg in 2021, while in 2022 (11.3 mg/kg), averaging 10.3 mg/kg over two years, and the soil fertility was very low (<30 mg/kg). During the tillering phase of spring soft wheat, the experimental variants for soil supply of nitrate nitrogen and available phosphorus nonsignificantly differed from the initial data mentioned above. Against the backdrop of the control treatment (no fertilizer application) during the heading period of spring wheat, the soil nitrate-nitrogen content was 12.0 mg/kg, and upon applying the half and maximum recommended doses of fertilizers, the soil's nitrate-nitrogen content enhanced to 13.8 and 14.5 mg/kg, respectively. In 2022, in the control treatment, the nitrate-nitrogen content was 14.3 mg/kg, while on the fertilized backgrounds, its content was higher (ranging from 16.1 to 19.6 mg/kg) in the soil.

On average, over two years, the soil supply of nitrate nitrogen on the mentioned backgrounds was 13.2, 15.0, and 17.1 mg/kg, respectively. During the grain-ripening phase of spring wheat in 2021, the soil nitrate-nitrogen content in the control variant was 5.6 mg/kg, with half of the calculated dose (7.7 mg/kg), and with the highest-calculated dose (8.4 mg/kg). In 2022, the values were 4.6, 12.9, and 17.2 mg/kg, respectively. On average, over two crop seasons, with the control treatment, the soil nitrate-nitrogen content was low (5.1 mg/kg). On backgrounds with a half and the utmost-calculated doses, it increased to 10.3 and 12.8 mg/kg, respectively. Thus, a more favorable nitrogen nutrition regime developed with the fertilized backgrounds.

In the experimental plots, the soil phosphorus availability was also low, i.e., in 2021, it was 4.0 mg/kg, while in 2022, the value was 6.5 mg/kg, averaging 5.3 mg/kg. During the heading phase of spring wheat, the requirement of soil mobile phosphorus with an unfertilized background was 5.1 mg/kg in 2021, 6.8 mg/kg in 2022, and, on average, 6.0 mg/kg. With a background of a half-calculated dose, it increased to 5.9, 9.8, and 7.9 mg/kg, respectively. In the background of the highest-calculated dose of mineral fertilizer, the values were 5.9, 9.7, and 7.8 mg/kg, respectively. During the ripening phase of spring wheat, the availability of soil phosphorus slightly decreased on the unfertilized background in 2021 (4.5 mg/kg), while 2.3 mg/kg in 2022, with an average of 3.4 mg/kg. In recent years, soil fertility has continued to decrease in Northern Kazakhstan. The soils of the Akmola region are poor in humus, nitrogen, and phosphorus, with humus content of 66.9%, 29.0%, and 4.1%, respectively, in the arable land area. The low content of quick hydrolyzable nitrogen was 53%, an average of 28.2%, and the high was 18.8% in arable lands. Low soil availability of mobile phosphorus showed 38.5%, average availability of 47.2%, and high income of 14.3% in the studied arable lands. Therefore, applying mineral fertilizers with different doses on diverse soils can increase the yield (Khusainov, 2019).

With a background of half of the calculated dose of mineral fertilizers, it increased in 2021 (5.0 mg/kg) and 2022 (8.9 mg/kg), with an average of 7.0 mg/kg. The soil background with a maximum-calculated dose of fertilization was 3.4, 5.5, and 4.5 mg/kg, respectively. Thus, in the spring wheat, the phosphorus nutrition regime improved with fertilized backgrounds. The research showed a significant influence of mineral nutrition levels on the formation of leaf area and photosynthetic activity in spring soft wheat lines. The flag leaf area of the spring soft wheat lines averaged9,900 m²/ha without the application of mineral fertilizers, 10,200 m²/ha with half the calculated dose of mineral fertilizers, and 12,300 m²/ha with the utmost-calculated dose of fertilizers. The total leaf area under these conditions was 13,900, 15,200, and 17,700 m²/ha, respectively (Figure 5). In the Almaly region, Kazakhstan, the grain crops productively used nitrogen with its partial application at the beginning of tillering and tubing, respectively, and at the third and

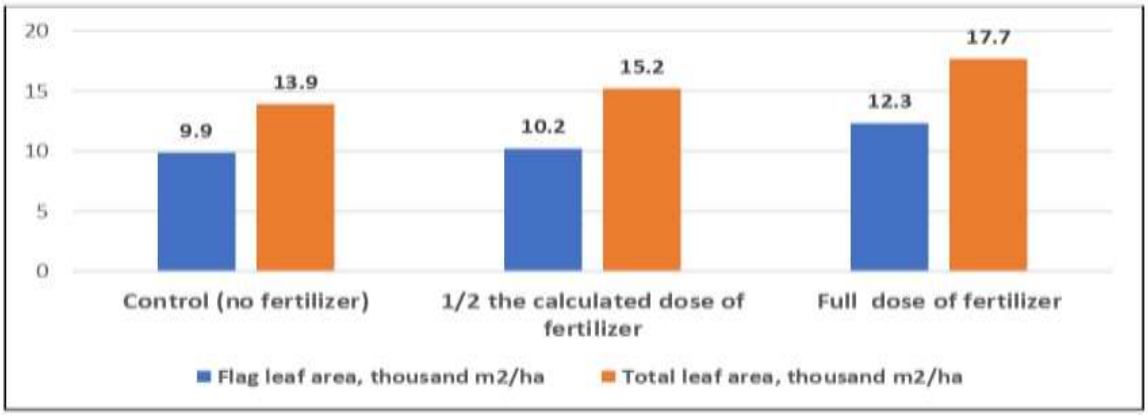

Figure 5. Flag leaf area and total leaf area of spring soft wheat lines (average for 2021–2022).

fourth stages of organogenesis. By using nitrogen fertilizers, significant varietal differences were also evident (Ramazanova *et al*., 2023).

The analysis of mid-early lines of spring soft wheat without mineral fertilizers (control variant) revealed the photosynthetic potential of the crop averaged 0.672 million m² per day, and the standard cultivar Omskaya-36 had a potential of 0.662 million m² per day. The spring wheat lines Erythrospermum 738, Lutescens 715 sp2/04, and Lutescens 814 sp2/09 exceeded the standard by 0.044–0.111 million m² per day. The photosynthetic potential for most spring wheat lines was at the standard level or even below. In the control group, the range of variation (R = 0.193) and the coefficient of variation (V = 8.62) revealed low variability for this trait. Net photosynthetic productivity varies significantly based on the leaf area parameters.

In the presented study, within the group of control plots, the average net photosynthetic productivity was 6.6 g/m² per day. The best performance resulted in the spring wheat lines Lutescens 821 sp2/08 (7.0), Lutescens 1206 sp2/19 (7.5), and Lutescens 715 sp2/04 (8.8), while most were either at or below the standard level. With this background, the value of the standard Omskaya 36 was 0.9%, and the photosynthetic active radiation use coefficient varied within the range of 0.7% to 1.3% for the wheat lines Erythrospermum 738, Lutescens 1148 sp2/09, and Lutescens 715 sp2/04. Based on this analysis, the net photosynthetic productivity and the photosynthetic active radiation utilization coefficient were informative (Figure 6). Experimental data from the Akmola region, Kazakhstan, exhibited the early-maturing genotypes' photosynthetic potential (1.064 million m^2 per day). Creating the photosynthetic potential of sowing depends on the development and formation of the leaf surface (Syzdykova, 2012). The net productivity of photosynthesis varies significantly depending on the parameters of the leaf area. This indicator characterizes the average efficiency of leaf photosynthesis (Nichiporovich, 1959).

With half of the calculated fertilizer dose, the average deviation within the group was 0.764 million m^2 per day and the value of 0.757 million m^2 per day for the standard cultivar Omskaya-36. Among the studied lines, the photosynthetic potential significantly exceeded the standard Omskaya-36, i.e., Lutescens 715 sp2/04 (0.953 million m^2 per day) and Erythrospermum 738 (0.814 million m^2 per day). The photosynthetic potential of most spring wheat lines was either at the same level as the control or lower. Applying half of the calculated fertilizer dose had a negligible impact on the variability of the photosynthetic potential, i.e., the variability range was 0.288, and the coefficient of variation was 9.68. The net productivity of photosynthesis with half of the calculated fertilizer dose had an average value of 6.9 g/m^2 per day within the group, ranging from 6.4 (Lutescens 821 sp2/08) to

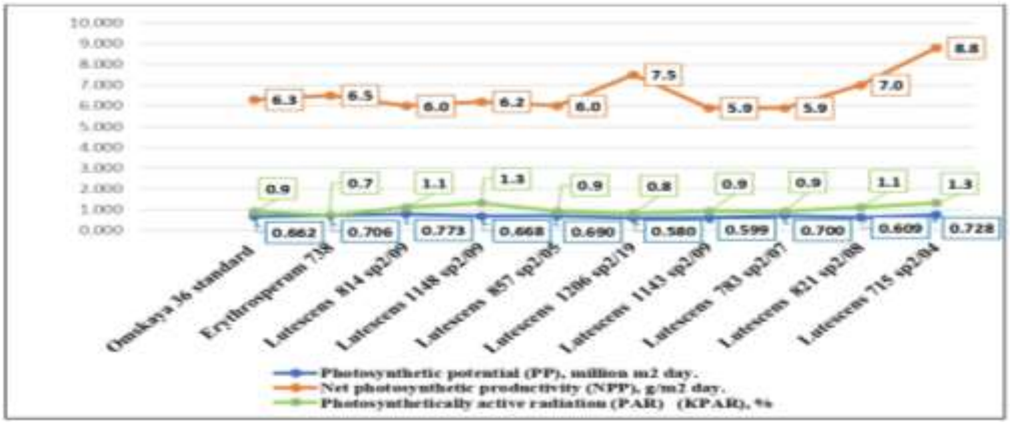

Figure 6. Photosynthetic parameters in mid-early lines of spring soft wheat, control background – with no fertilizers (average for 2021–2022).

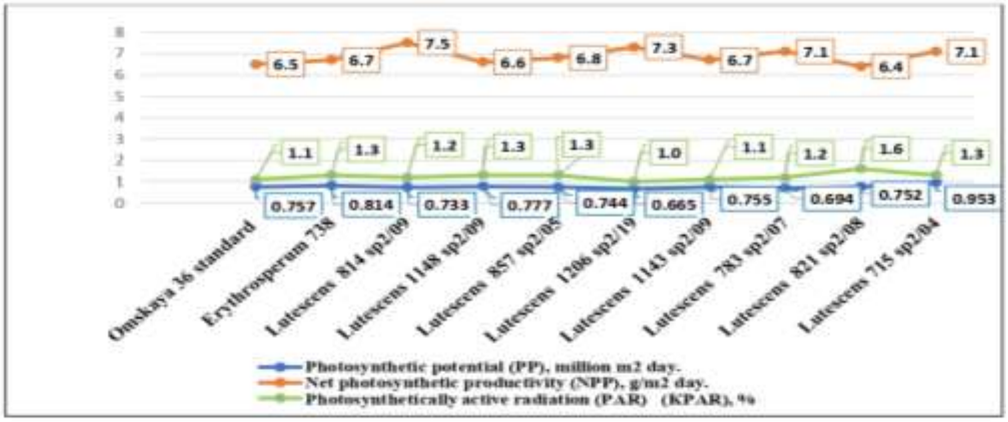

Figure 7. Photosynthetic parameters of mid-early spring soft wheat lines, background – half-calculated dose of fertilizers (average for 2021–2022).

7.5 (Lutescens 814 sp2/09). In this variant, most spring wheat lines significantly exceeded the standard cultivar Omskaya-36 (6.5), except for lines Lutescens 821 sp2/08 (6.4) and Erythrospermum 738 and Lutescens 1148 sp2/09 (6.7 g/m^2). The variability range and the coefficient of variation for this trait were weak. With half of the calculated mineral fertilizer dose, most studied lines exceeded the standard cultivar Omskaya 36 by 1.1%, ranging from 1.2% (Erythrospermum 738 and Lutescens 783 sp2/07) to 1.6% (Lutescens 821 sp2/08). However, moderate variability emerged for this parameter, i.e., V = 12.6 and R = 0.6 (Figure 7). The application of mineral fertilizers showed a significant effect on the intensity of increasing the photosynthetic potential in the Ulyanovsk region, Russia. The highest value of photosynthesis productivity was against the background of the use of mineral fertilizers, with the maximum values of the net productive potential observed in the earing phase, that is, during the period of the maximum development of the leaf surfaces in spring wheat (Nikitin, 2017). On the fertilized background in the Altai Territory, Russia, the average photosynthetic potential for wheat vegetation amounted to 1.98 million m^2 per day, which exceeded the control by 38% (Khizhnyakova and Chernetsova, 2014).

With a background of the highest-calculated fertilizer dose, the average value was 0.960 million m² per day. Notably, all the studied spring wheat lines significantly exceeded the standard cultivar Omskaya 36 (0.841), ranging from 0.896 to 1.048 million m² per day (Figure 8). Treating the utmost-calculated fertilizer dose had a weak impact on the variability of photosynthetic potential, with a range of variation (R = 0.207) and coefficient of variation (V = 6.68). With the maximum fertilizer dose, the net photosynthetic productivity had an average group value of 6.7 g/m² per day. With this background, all the wheat lines were below the standard cultivar Omskaya 36 (7.6), except for the line Erythrospermum 738 (7.8 g/m² per day), which significantly exceeded it. The values for the range of variation were R = 2.5, and the coefficient of variation was V = 11.6%. The utilization of photosynthetic active radiation coefficient increases to 1.3% with the highest mineral fertilization. With this background, all the spring wheat lines significantly exceeded the standard cultivar Omskaya 36 (1.0%) by 1.1% (Lutescens 1206 sp2/19) to 1.4% (Lutescens 1148 sp2/09, Lutescens 857 sp2/05, Lutescens 783 sp2/07, and Lutescens 715 sp2/04) (Figure 8).

The photosynthetic potential of spring wheat lines on the unfertilized soil averaged 0.672 million m² per day, with half of the calculated dose at 0.764 million m² per day and with the utmost calculated dose at 0.960 million m² per day. The coefficient of photosynthetic radiation utilization increased from 1.0 in the control to 1.2 and 1.3 on fertilized backgrounds. The promising results indicate that the number of nodal roots significantly varies based on the experimental variants and the fertilizer backgrounds (Figure 9). With background of the control variant, the number of nodal roots amounted 3.3 pieces per plant, while for the wheat lines Lutescens 814 sp2/09, Lutescens 1148 sp2/09, Lutescens 857 sp2/05, Lutescens 783 sp2/07, and Lutescens 715 sp2/04, the trait values were 3.8, 3.8, 3.6, 4.0, and 4.3 pieces per plant, respectively. The excess over the standard cultivar ranged from 9.6% to 30.3%, and the highest number of nodal roots (4.3 pieces per plant) resulted in the spring wheat line Lutescens 715 sp2/04, which also exceeded the standard cultivar by 30.3%. The rest of the wheat lines had several nodal roots either at the standard level or below it.

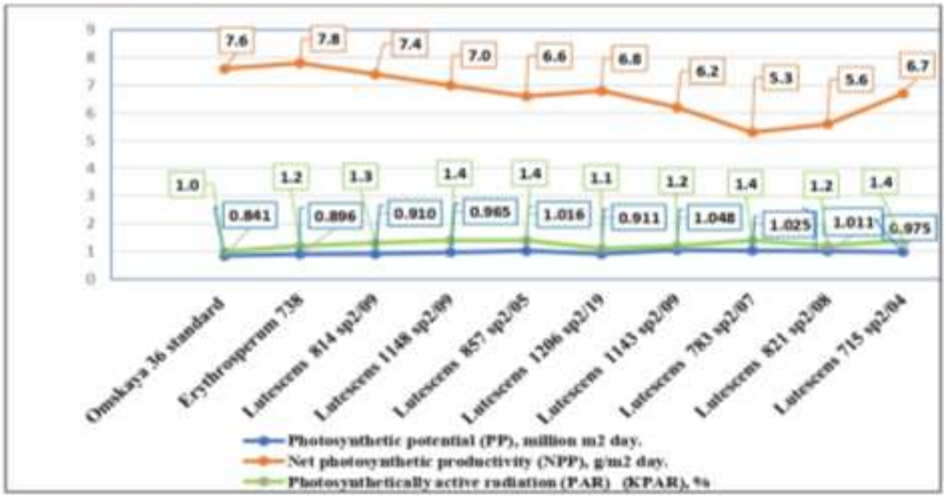

Figure 8. Photosynthetic parameters of mid-early lines of spring soft wheat, background – maximum-calculated fertilizer dose (average for 2021–2022).

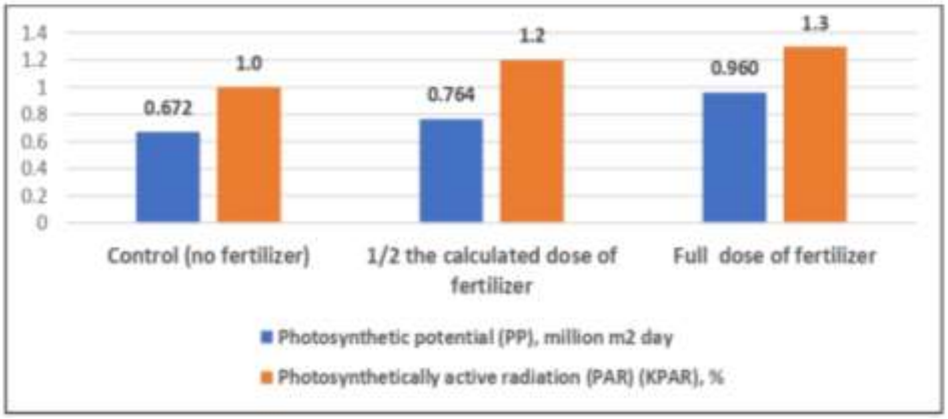

Figure 9. Photosynthetic potential of spring wheat lines in the mid-early group (average for 2021–2022).

With a soil background of a half dose of fertilizers, in the standard cultivar, the number of nodal roots was 3.8 pieces per plant. With the wheat lines Erythrospermum 738, Lutescens 814 sp2/09, Lutescens 1148 sp2/09, Lutescens 857 sp2/05, Lutescens 1206 sp2/19, and Lutescens 715 sp2/04, the trait was higher at 4.8, 4.8, 5.0, 4.7, 4.8, and 5.0 pieces per plant, respectively. The excess over the standard cultivar ranged from 7.9% to 31.6%, with the highest number of nodal roots (5.0 pieces per plant) observed in the spring wheat lines Lutescens 1148 sp2/09 and Lutescens 715 sp2/04, exceeding the standard cultivar by 31.6%. The rest of the wheat lines had several nodal roots either at the standard level or below it.

The soil background of a maximum dose of mineral fertilizers, the number of nodal roots in the standard cultivar was 4.5 pieces per plant. For the lines Erythrospermum 738, Lutescens 814 sp2/09, Lutescens 1148 sp2/09, Lutescens 1206 sp2/19, Lutescens 783 sp2/07, and Lutescens 715 sp2/04, it was higher at 5.0, 6.3, 4.9, 5.3, 5.8, and 6.2 pieces per plant, respectively. The excess over the standard cultivar ranged from 8.2% to 40.0%, with the highest number of nodal roots (6.3 pieces per plant) observed in the Lutescens 814 sp2/09 line, exceeding the standard cultivar by 40.0%. The rest of the spring wheat lines had several nodal roots either at the standard level or below it. With the background of the highest dose of fertilizers, the number of nodal roots for the spring soft wheat lines averaged 5.2 per plant, which was 1.6 pieces per plant more than on the background with the control variant (no fertilizers).

With a soil background of no mineral fertilizer application (control), a low trait variation occurred with a coefficient of variation of V = 9.87 and R = 1.3. However, with soil backgrounds of half and maximum doses of mineral fertilizer application, the variation for the said trait increased to V = 11.71 to 13.55 and R = 2.0, indicating the varying responses of studied wheat lines to the level of agricultural intensification. The most responsive spring wheat lines to mineral nutrition were Lutescens 814 sp2/09, Lutescens 1148 sp2/09, and Lutescens 715 sp2/04. Their number of nodal roots enhanced from 3.8, 3.8, and 4.3 pieces per plant from the control variant to 4.8, 5.0, and 5.0 pieces per plant with a background of half of the calculated dose of fertilizers, and further to 6.3, 4.9, and 6.2 pieces per plant (Table 1). The intensive development of the root system depends on the factors of soil fertility caused by its active growth. Between the phases of earing and full ripeness, the mass of the root system rose by 24% due to the expansion of secondary roots. In the tillering phase, soil temperature, nitrogen, phosphorus, and potassium content in the soil, and the presence of productive moisture in the Saratov region,

Table 1. The number of nodal roots in spring wheat lines (average for 2021–2022).

Spring wheat cultivar & lines	Bolting Phase					
	No Fertilization (Control) (#)	Increase over the standard (%)	Half dose of Fertilization (#)	Increase over the standard (%)	Full Dose of Fertilization (#)	Increase over the standard (%)
Standard cultivar (Omskaya 36)	3.3	-	3.8	-	4.5	-
Erythrospermum 738	3.5	6.1	4.8	26.3	5.5	22.2
Lutescens 814 sp2/09	3.8	15.2	4.8	26.3	6.3	40.0
Lutescens 1148 sp2/09	3.8	15.2	5.0	31.6	4.9	8.2
Lutescens 857 sp2/05	3.6	9.1	4.7	23.7	4.4	-2.2
Lutescens 1206 sp2/19	3.4	3.0	4.8	26.3	5.3	17.8
Lutescens 1143 sp2/09	3.4	3.0	3.7	-2.6	4.7	4.4
Lutescens 783 sp2/07	4.0	21.2	4.1	7.9	5.8	28.9
Lutescens 821 sp2/08	3.0	-9.1	3.7	-2.6	4.3	-4.4
Lutescens 715 sp2/04	4.3	30.3	5.0	31.6	6.2	37.8
Average	3.6		4.4		5.2	
$LSD_{0.05}$	0.2		0.2		0.3	
Lim (Limit)	3.0-4.3		3.7-5.0		4.3-6.3	
R (Range)	1.3		1.3		2.0	
Coefficient of Variation (V %)	9.87		11.71		13.55	

Russia, mainly influenced the root system enhancement of spring wheat (Medvedev *et al*., 2013). The number of nodal roots revealed varietal differences, with significant influences from both environmental conditions and genetic characteristics of plants. It was also apparent against a background without mineral fertilizers that the variability of nodular roots in wheat shows that the trait variation in the phase of entering the tube was less (2.9%) (Syzdykova *et al*., 2018).

CONCLUSIONS

The latest research on the influence of mineral fertilizer application on the spring soft wheat leaf area photosynthetic activity, root development, and productivity showed that the genotypes have varied responses to the different fertilizer rates, which might be due to their diverse genetic makeup and biological potential. Furthermore, the most informative indicator was the total leaf area under the mineral nutrient conditions. The number of nodal roots in the context of fertilizer application demonstrated higher activity influencing the grain yield.

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