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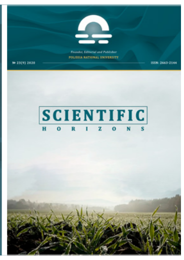

Efficiency of leaf fertilisers in complex fertilisation of cereals on southern chornozems of Northern Kazakhstan

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Abstract. The study aimed to evaluate the effect of foliar feeding on the physiology, yield and economic efficiency of spring wheat in Northern Kazakhstan. The field trials were conducted during the growing season of 2024 (May-August) at the experimental plot of Kokshetau University named after Sh. Ualikhanov and were aimed to assess the agricultural, ecological and economic efficiency of different schemes of foliar feeding of spring wheat. The study included five variants of the experiment, which differed in the composition and frequency of fertiliser application, including urea, microelements and biostimulants. The variants with foliar treatments showed a stable advantage in agrophysiological parameters, especially in hot and dry weather conditions, at a temperature of about +33°C and air humidity of 30-35%. The highest results were obtained with two-time foliar feeding (variant B5), where the yield reached 43.2 c/ha,

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which exceeded the control by 5.6 c/ha (14.9%). The weight of 1,000 grains increased to 45.6 g, the productive density to 417 stems/m2, and the number of ears per ear to 16.5. The duration of the flag leaf functioning in this variant reached 14 days, and the chlorophyll level remained high during the filling phase. There was a significant reduction in leaf rust (down to 14.5%) and a 15% increase in the share of milled grain. The economic analysis demonstrated that option B5 provided the highest income (129,600 tg/ha) with a payback ratio of 2.1 and an economic effect of 18,000 tg/ha. The other options provided a yield increase of 3.3 to 4.7 cwt/ha with payback periods ranging from 1.6 to 1.9. The data confirm the expediency of integrating phase-selected foliar fertilisation into wheat cultivation technologies in the risky farming zone. Comparing experiments in different years in terms of moisture levels, it can be concluded that, provided there is sufficient moisture, foliar feeding is more effective when combined with the main application of macronutrients (nitrogen and phosphorus)

Keywords: physiological activity; productive stems; chlorophyll content; vitality index; microelements; spring wheat; yield

INTRODUCTION

The research relevance is determined by the need to improve agronomic approaches to soft spring wheat cultivation in Northern Kazakhstan. The agroclimatic features of the region, including frequent periods of drought, sharp fluctuations in vegetation period temperatures and unstable moisture supply, made it difficult to realise the biological potential of varieties. In the context of declining efficiency of traditional cultivation methods, the development of alternative strategies for managing the physiological state of plants became particularly relevant. Foliar feeding was seen as one of the most promising ways to quickly deliver nutrients to critical phases of organogenesis, helping to maintain the photosynthetic apparatus and prolong the functioning of the flag leaf. The problem of the study was the limited adaptability of standard foliar nutrition schemes to the soil and climatic conditions of the North Kazakhstan zone.

According to T.Z. Aidarbekova *et al.* (2024) differentiated mineral nutrition on the chornozems of Northern Kazakhstan, which contributed to the growth of flag leaf photosynthetic activity, which was reflected in an increase in the chlorophyll index and, as a result, in an increase in yield. The greatest effect was observed with a balanced nitrogen supply in the phase of tube emergence. The publication by S. Turebayeva *et al.* (2022) noted that when direct sowing in the arid conditions of Southern Kazakhstan, phased fertilisation provided an economically justified increase in winter wheat yield. Late treatments combined with minimal inputs helped to improve the spike structure and reduce the risk of hollowing. A study by N.O. Turganbayev *et al.* (2023) showed that under no-till conditions, the highest productivity indicators were associated with early micronutrient supply. This reduced the yield variability between replications and increased the protein content in the grain. R. Drăghici *et al.* (2022) described how micronutrient sheet fertilisers on sandy soils improved rye development, especially in conditions of moisture deficit. The benefits were expressed in sustainable biomass growth, slower leaf senescence, and uniform formation of productive shoots.

The analysis of L. Crista *et al.* (2024) revealed that when applying complex foliar fertilisers to maize, the main performance indicators were the Soil Plant Analysis Development (SPAD) index and the weight of the aerial part. The direct relationship between the dosage of trace elements and the uniformity of generative organs indicated the stability of the physiological status of plants. S. Šeremešić *et al.* (2022) emphasised that crop rotation with the use of leaf fertilisers on chornozems led to an improvement in the phytosanitary condition of soybeans. The impact of weather stress was significantly reduced, and productivity remained high even in years with limited rainfall. The review by L. Marcinska-Mazur and M. Mierzwa-Hersztek (2023) emphasised the high efficiency of integrated nutrition schemes for wheat and rapeseed, combining root and foliar feeding. This strategy significantly increased not only the yield, but also the technological parameters of grain, including crude protein content and vitreous content. According to R.A. Paunescu *et al.* (2023), intensive crop rotations with a well-thought-out nutrition system provided an increase in wheat yields by increasing productive bushiness and ear length. In addition, at optimal fertiliser doses, there was an improvement in the morphological characteristics of the stem, which increased lodging resistance.

Materials by G. Macra and F. Sala (2022) recorded a significant variation in nitrogen use efficiency when combining mineral fertilisers with foliar treatments. The maximum return per unit of nitrogen applied was achieved in schemes that included stimulation of the leaf apparatus in the phase of intensive growth. According to the results of S. Dhaliwal *et al.* (2022), bioenrichment through micronutrient foliar treatments contributed to an increase in the content of iron, zinc and selenium in field crops. It is noted that the use of such agricultural technologies helps to increase yields and improve the chemical composition of grain, including the content of protein and trace elements. The study by R. Gaj *et al.* (2023) demonstrated that proper management of nitrogen nutrition in triticale ensured high efficiency of its assimilation, which was reflected in a decrease in the residual nitrate content in the soil and a stable level of yield. Schemes with controlled fractional fertilisation combined with foliar nutrition correction proved to be effective. A synthesis review by I. Varga *et al.* (2022) addressed nitrogen management strategies in sugar beet but notes the universality of approaches applicable to cereals. Among the most effective methods were foliar corrections in the context of a balanced basic nutrition, which help to maximise the nitrogen use factor by plants.

However, the effectiveness parameters of different types of foliar feeding, which differ in composition, time and frequency of application, were not studied in detail. The question of the impact of such treatments on plant resistance to pathogens, photosynthetic activity under stress and the duration of flag leaf functioning remained open. In addition, there was no comprehensive assessment of the agronomic and economic effectiveness of these practices, which prevented the development of sound recommendations for adaptive wheat cultivation in an unstable climate. The study aimed to determine the optimal schemes of foliar feeding of spring wheat to increase its productivity and sustainability in Northern Kazakhstan.

MATERIALS AND METHODS

The field study was conducted during the growing season of 2024 (May-August) based on the educational and experimental plot of Kokshetau University named after Sh. Ualikhanov in Kazakhstan. The climate is characterised as temperate continental, with a high temperature range and insufficient precipitation during the growing season. The average monthly air temperature ranged from +15.8°C in May to +28.3°C in July, with temperatures rising to +33°C on some days, which, combined with a total precipitation of 138 mm per season, met the criteria for atmospheric drought. Soil conditions of the site are represented by southern chornozems with humus content in the range of 3.6-3.8%, slightly acidic reaction of the environment (pH 6.8), nitrogen content of 14.3 mg/kg, phosphorus of 17.8 mg/kg, and potassium of 38.6 mg/kg. The particle size distribution is light loamy. These characteristics provide a favourable agricultural background subject to additional nutrition.

The study was conducted on soft spring wheat of the Stepnaya 62 variety, zoned in Northern Kazakhstan. The variety Stepnaya 62 was chosen for its high adaptation to the agro-climatic conditions of Northern Kazakhstan and stable productivity. The trial included two factors: main fertilisation and foliar application. The first factor was the application of a complex mineral fertiliser at a dose of $N_{60}P_{40}K_{20}$ for pre-sowing cultivation. The second factor included five variants of foliar treatments: in variant B1, no foliar feeding was carried out, and it was used as a control. In variant B2, a 10% urea solution was applied during the tillering phase. Variant B3 involved the application of a complex microfertiliser containing boron (150 g/l), zinc (75 g/l) and manganese (100 g/l) at the tube stage. Variant B4 included treatment with a biostimulant based on amino acids and humates during the earing phase. Variant B5 combined urea treatment in the tillering stage and a biostimulant in the earing stage. The experiment was designed using the randomised block design in triplicate. The registered area of each plot was 10 m^2. All agrotechnical practices were conducted in the same way in all variants: the crop predecessor was pea, the main treatment included ploughing by 25-27 cm followed by cultivation, sowing was conducted at the end of May with a seeding rate of 550 germinating seeds/m^2. Herbicidal protection in all variants was provided by a 2.4-D-based preparation at the beginning of tillering.

Productive elements were recorded at full maturity manually at three plots within each plot. The productive density (pcs/m^2) and the number of spikelets per plant were determined manually at three sites. The average number of spikelets per plant (pcs.), weight of 1,000 grains (g) and yield (c/ha) were determined. The weight of 1,000 grains were measured on a laboratory balance AXIS ADG-200 (Poland), in triplicate, and the yield was calculated using the formula (1):

$$Y = \frac{M \cdot 10^4}{S} \cdot \frac{1}{100}, \quad (1)$$

where Y – yield; hwt/ha; M – grain weight per plot; kg; S – plot area; m^2.

The chlorophyll content in the flag leaf was assessed during the grain filling phase using a portable chlorophyllometer SPAD-502Plus (Konica Minolta, Japan). The readings were taken in the morning (8:00-10:00) from ten plants per plot in the middle of the flag leaf length. The obtained values were averaged and used to analyse the physiological activity of the leaf. Phytosanitary resistance of plants was assessed at the stage of milk ripeness by visual diagnostics. The manifestations of leaf diseases (brown and yellow rust, septoria) were noted, using a 5-point scale, where: 0 – no lesions, 1 – up to 5% of the leaf surface, 2 – up to 15%, 3 – up to 35%, 4 – up to 55%, 5 – more than 75%. The assessment was conducted by a committee of three experts from the Department of Agriculture and Biological Resources, each of whom had experience in phytosanitary diagnostics. The data were averaged over all observations within the same variant. The lesion index was calculated as a weighted average score based on visual assessments using formula (2):

$$I = \frac{\sum(a \cdot b)}{n}, \quad (2)$$

where a – lesion score; b – number of plants with the score; n – number of examined plants.

The damage to the ears (%) was recorded separately by visual inspection during the wax ripeness phase. The delay in the onset of disease symptoms was estimated as the difference in days between the first manifestation and the control variant. The duration of the flag leaf functioning under stressful weather conditions was determined visually, by the time more than 50% of its area remained green. The countdown started from the beginning of milk ripeness to the moment of visual yellowing. The counting was conducted at intervals of 2-3 days in the morning. Variants with longer leaf retention were considered to be physiologically more resistant to weather stress (overheating, drought). The agronomic and economic efficiency was assessed by gross income (tg/ha), incremental costs (tg/ha), net income and return on investment (ROI). The latter was calculated using formula (3):

$$K_r = \frac{D_{var} - D_{contr}}{Z_{var} - Z_{contr}}, \quad (3)$$

where K_r – investment return ratio; D_{var}, D_{contr} – gross income in variant and control; Z_{var}, Z_{contr} – costs in variant and control. The yield increase (tonnes per hectare) was calculated based on the average market price for wheat, with costs including the cost of inputs, labour and depreciation of equipment. All calculations were made per 1 ha.

The results of the experiments were statistically processed by one- and two-factor analysis of variance using Statistica 12.0 software (USA). The reliability of the differences between the variants was assessed by the significance criterion ($p < 0.05$), and coefficients of variation and standard errors were calculated. The authors adhered to the standards of the Convention on Biological Diversity (1992).

RESULTS

Effect of foliar feeding on productivity elements of durum wheat. Yields varied widely, from 37.6 c/ha in the control (B1) to 43.2 c/ha in the variant with two foliar applications (B5), which corresponded to a 15% increase compared to the background level. A single application of urea in the tillering phase (B2) provided a moderate increase in yield to 40.9 c/ha, or 8.8% higher than the control. The use of a micronutrient complex (boron, zinc, manganese) in the tube stage (B3) resulted in a yield of 41.6 c/ha, which was 10.6% higher than the control. The use of a growth biostimulant, including humates and amino acids (B4), had a pronounced positive effect, with a yield of 42.3 c/ha, or 12.5% higher than B1. The most significant results were obtained with double foliar treatment (B5), which combined early application of urea and subsequent application of a biostimulant, with a maximum yield of 43.2 c/ha.

Leaf fertilisation had a complex effect on the structure of the crop. The number of productive stems per square metre in the treated variants was 18-22 units higher than in the control. Thus, in B1, an average of 383 productive stems/m^2 was recorded, while in variants B3, B4 and B5 this value reached 401, 405 and 417, respectively. Thus, the increase in stem density was accompanied by an improvement in the spatial structure of the crops, which had a favourable effect on the formation of the ear. The number of spikelets per ear also varied depending on the nutrition scheme. In the control, it averaged 15.4 spikelets, and in the variants with microelements and biostimulants (B3, B4), 16.1 and 16.3 spikelets, respectively. The maximum value of 16.5 pcs/ear was recorded in variant B5. These data indicate that follicle nutrition stimulated the development of generative organs, especially in the phase of tube formation.

The weight of 1,000 grains, one of the most sensitive indicators of plant nutrition, also changed significantly under the influence of fertilisation. If in the variant without additional treatment this indicator was 43.4 g, then in B3 and B4 it reached 44.8 g and 45.1 g, respectively. The highest weight was recorded in the B5 variant (45.6 g), which indicated a more intensive grain filling. Thus, biostimulants and combined nutrition schemes contributed to the formation of high-grade grains with a high specific weight. Additional confirmation of the positive impact of leaf fertilisers was provided by observations of the uniformity of plant development. In variants B1-B2, significant fluctuations in stem height and heterogeneity in developmental stages were observed, especially under stressful conditions of late tillering and heat. Whereas in variants B3-B5, plants were distinguished by a levelled stem, synchronous development and more uniform grain filling. This reduced intra-field variability and ensured a more uniform maturation of the crop (Table 1).

***Table 1**. Changes in productive traits of soft wheat under the influence of different foliar nutrition schemes*

Variant	Solution description	Yield, hwt/ha	Productive stems, pcs/m2	Spikelets per ear, pcs	Weight of 1,000 grains, g
B1	Without foliar feeding (control)	37.6	383	15.4	43.4
B2	Urea 10% (tillering phase)	40.9	394	15.9	44.2
B3	Trace elements (B+Zn+Mn, tube output)	41.6	401	16.1	44.8
B4	Biostimulant (amino acids + humates)	42.3	405	16.3	45.1
B5	Double application (tillering + mowing)	43.2	417	16.5	45.6

***Source:** compiled by the authors*

Thus, the study confirmed that foliar fertilisation, especially in the form of biostimulants and micronutrient complexes, has a positive effect on yield and its structural parameters. The increase in productive bushiness, ear development and grain filling were significantly improved in the variants with combined or repeated application. Particularly high efficiency was demonstrated by variant B5, which implements the principle of layered plant nutrition in key phases of ontogeny.

Chlorophyll a content (SPAD) in different foliar application patterns. One of the key indicators used in assessing the physiological state of crops was the chlorophyll content in the leaves, measured in SPAD units. This parameter is closely related to the functional state of the photosynthetic apparatus and reflects the reaction of plants to the supply of nutrients. In the control variant (B1), where no foliar feeding was applied, the chlorophyll content was 38.7 SPAD, indicating moderate chloroplast activity and possible restriction of access to nitrogen during critical phases of the growing season. The variant with urea application in the tillering phase (B2) provided an increase in chlorophyll content to 42.3 SPAD, indicating partial compensation for nitrogen deficiency and improvement of photosynthetic activity. The use of a microelement mixture in the phase of entering the tube (B3) contributed to an increase in this indicator to 45.2 SPAD, which can be explained by the role of zinc, boron and manganese in the regulation of photosynthetic processes, amino acid synthesis and the functioning of enzymatic systems. In the variant with the use of a biostimulant based on humates and amino acids (B4), the chlorophyll content reached 47.1 SPAD, indicating an increase in metabolism, improved membrane permeability and increased physiological activity of plants. The highest values were recorded at the two-time treatment (B5) – 49.5 SPAD, which is 27.9% higher than the control level. Thus, foliar feeding, especially in combination, provided a significant increase in photosynthetic potential, which is key in the formation of the crop.

The content of nutrients in the aboveground mass of plants also varied depending on the fertilisation scheme. In the control (B1), the content of total nitrogen was 2.65%, phosphorus – 0.32%, and potassium – 1.41%. In the variants with foliar fertilisers, these indicators increased: in B2 to 2.77%, 0.34% and 1.46%, in B3 to 2.89%, 0.35% and 1.49%; in B4 to 2.95%, 0.36% and 1.51%; and in B5 to 3.02%, 0.37% and 1.54%, respectively. This confirms the effectiveness of foliar nutrition in conditions of limited availability of elements in the soil solution, especially in the case of drought and soil compaction in the upper horizons. In addition, an increase in the concentration of elements in tissues indicates a more active transport and assimilation of nutrients in the phases of intensive growth. A complex indicator of the general physiological state of plants was the viability index, which considers a set of parameters of turgor, colour, development, and the presence of stress symptoms. In the control, this index was 0.74. In variant B2 (urea), the index value reached 0.79, with the use of trace elements (B3), it increased to 0.83, with the use of biostimulants (B4) to 0.87, and in variant B5, it reached 0.89. Such values correspond to a high physiological tone of plants and indicate resistance to external influences. The treated variants demonstrated not only better leaf colour but also longer preservation of green mass. In variants B4 and B5, under the conditions of July heat (daytime temperatures up to +33°C), the leaves remained active longer, without showing signs of anthocyanin colouration and premature ageing, which is relevant for full grain filling.

A separate observation concerned the duration of the active growing season. In the variant without foliar treatment, earlier yellowing and death of the leaves of the upper tier were observed, which reduced the life of the photosynthetic apparatus by 4-5 days. In the variants with foliar treatment, especially B5, the period of green activity lasted until the middle of grain filling, ensuring full photosynthesis in the crucial time for yield. In addition, these variants showed a more uniform colour of plants, stem density and the absence of depressed areas, which are typical for the control (Fig. 1).

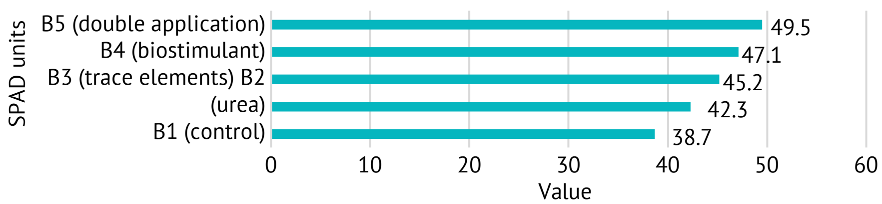

***Figure 1**. Intensity of chlorophyll accumulation depending on the methods of foliar feeding*
***Source:** compiled based on Formula (1)*

Thus, foliar feeding has proven to be efficient for increasing the physiological activity of durum wheat. Biochemical shifts towards an increase in chlorophyll, nitrogen, phosphorus and potassium in plant tissues, as well as visually observed stress resistance, indicate the effective impact of the used products. A particularly pronounced effect was observed when the combined strategy was applied in layers, which provided the highest level of all the physiological and biochemical parameters studied. This makes it possible to consider variant B5 as the most effective in temperate continental climate and southern chornozems, especially in years with limited water supply. The data obtained confirm the need to include folate nutrition in the overall fertilisation system of cereals under intensive cultivation technology.

The effect of foliar feeding on disease resistance and physiological parameters of leaves. In the control variant (B1), where leaf nutrition was not carried out, the level of leaf damage by rust and septoria was the highest, with an average of 26.4% of the leaf area showing visually pronounced symptoms. The intensity of the damage was also maximum: the average depth of necrosis on the affected leaf reached 3.2 points on a 5-point scale, and the flag leaf preservation index did not exceed 0.62. The presence of a significant proportion of damaged leaves in the phase of active photosynthesis negatively affected grain formation, reducing the efficiency of the filling phase, as evidenced by a decrease in the weight of 1,000 grains and the number of productive ears in this variant. With a single application of urea (B2), the degree of damage decreased to 21.3%, and the intensity of symptoms decreased to 2.7 points. The flag leaf preservation index increased to 0.7, which indicates a partial increase in physiological resistance due to improved nitrogen nutrition, although the effect cannot be considered stable and complete. The delayed onset of pathogenesis symptoms compared to the control was about 2 days.

A more pronounced reduction in disease incidence was observed with the use of a microelement complex (B3): the proportion of the affected leaf surface was 16.1%, and the visual lesion index decreased to 2.2 points. The flag leaf safety index reached 0.76. This result is due to the fact that zinc and manganese are actively involved in lignin synthesis and strengthening of cell walls, limiting the penetration of fungi, while boron regulates the formation of the epidermis and reduces the number of stomata of the main gates of pathogen penetration. The delay in symptom onset was 4-5 days compared to B1. In the variant with the use of a biostimulant (B4) containing humates and amino acids, the degree of damage was 17.4%, and the intensity of symptoms was 2 points. There was a clear effect of preserving the flag list (index 0.78) and slowing down the development of the lesion: the delay factor was 5 days on average compared to the control. This effect is associated with the activation of the synthesis of phytoalexins and other secondary metabolic compounds with fungistatic effects and regulating the antioxidant activity of tissues.

However, the best results were recorded in the B5 variant with a double application of only 14.5% of the affected surface, with a visual lesion index of 1.7 points and a flagging index of 0.81. This is 11.9 percentage points and 1.5 points below the benchmark, respectively. This decrease indicates a synergy between the early stimulating effect of nitrogen and the subsequent activation of immune and anti-stress mechanisms under the influence of biostimulants. The delay in the onset of primary symptoms was 7 days on average, which completes critical phases of plant ontogeny without significant limitation of photosynthetic activity. In addition to assessing the area of damage, there was a difference in the speed of symptom development. In the control, the first signs of rust were recorded at the end of the tube, and intensive spreading began from the earing phase. In the treatment variants, especially B4 and B5, the onset of symptoms was shifted to later dates (5-7 days). This meant not only a reduction in infection intensity, but also a shift in pathogenesis to later stages, when the impact on yield becomes less critical. Visual assessments also confirmed better preservation of the upper tier of leaves, especially the flag leaf, which remained green in the B5 variant until full maturity in 72% of plants, compared to 49% in the control.

In addition, cases of ear infections (mainly Fusarium) were recorded, especially in conditions of high humidity in July. Although the total number of infected ears did not exceed 4.8% in the control variants, in the plots with foliar nutrition, this indicator remained at the level of 2.4-3.2%. At the same time, the severity of symptoms (discolouration, underdevelopment of grain, hollow spikelet) in variants B3-B5 was significantly lower, which further confirms the strengthening of generative protection. Visually, such ears retained their full shape, and the damage more often affected no more than 1-2 grains, as opposed to 4-5 in the control. The analysis of the inter-variant difference showed that under the same agricultural technology, the main factor limiting the development of pathogens was not the direct fungicidal effect of substances, but an increase in the nonspecific resistance of plants. It was the improvement of nutrition, photosynthesis, and the synthesis of structural and protective metabolites under the influence of microfertilisers and biostimulants that created the conditions for preventing the mass spread of infections. Variant B5, which combined nitrogen and humic stimulation, provided the most complete implementation of this protective mechanism (Table 2).

***Table 2**. Indicators of resistance and leaf viability under different foliar nutrition schemes*

Variant	Leaf damage, %	Defeat index (points)	Saving the flag list	Delayed onset of symptoms, days	Spikelet damage, %
B1 (control)	26.4	3.2	0.62	0	4.8
B2 (urea)	21.3	2.7	0.7	2	4.1
B3 (trace elements)	16.1	2.2	0.76	4	2.9
B4 (biostimulant)	17.4	2	0.78	5	3.2
B5 (double application)	14.5	1.7	0.81	7	2.4

***Source:** compiled based on Formula (2)*

Thus, phytosanitary monitoring data showed that foliar feeding, especially in a combined scheme (double application), not only increases plant productivity but also contributes to the formation of a sustainable agrophytocenosis. This is especially relevant in conditions where chemical protection may be limited for economic or environmental reasons. The use of physiologically active substances reduces the pesticide load and, at the same time, increases the biological resistance of crops, which makes this technique a promising element of an integrated crop protection system.

Duration of flag list operation in stressful weather conditions. In the variants without foliar feeding (B1), plants showed low agroecological stability. Under moisture deficit and high air temperature in the tillering and tube growth phase, yellowing of the lower tier of leaves, reduced turgor and signs of photosynthetic activity inhibition were observed already in the first decade of development. These plants were distinguished by uneven developmental stages, lower height, and pronounced stem spotting. The duration of flag leaf functioning in the earing phase did not exceed 9-10 days, which limited grain filling and reduced the weight of 1,000 grains. In the same weather conditions, the variants with leaf dressing demonstrated significantly higher resistance. This was especially evident in variants B3 (microelements) and B5 (double application), where plants retained turgor even at air temperatures above +32°C, maintained a bright colour, did not show an anthocyanin reaction and less often showed leaf curl. In these variants, the flag leaf remained functional for up to 13-14 days, ensuring active photosynthesis throughout the entire grain filling period.

According to meteorological data, the key climatic stress factors occurred during the earing and earing phase: average daily air temperatures exceeded +29°C, and relative humidity dropped to 30-35%. Under these conditions, the control variant showed a rapid decrease in the SPAD level of chlorophyll and visual signs of leaf apparatus degradation. While in variants B4 and B5, the chlorophyll content remained at a high level, indicating stabilisation of metabolism and maintenance of metabolic activity. The analysis of morphological and physiological reactions showed that the effectiveness of foliar feeding was most pronounced under extreme weather conditions. Under hot and dry weather conditions, the difference in yield between the control variant and B5 was 5-6 c/ha, while under milder temperature conditions, the effect was weaker. This indicates that the effectiveness of foliar nutrition is particularly high in stressful years, when the crop experiences a sharp limitation of water or heat balance.

With a single application of fertiliser (e.g. B2 or B3), a temporary positive effect was observed due to increased nutrition and photosynthesis, but it was less stable compared to variant B5. The latter ensured the maintenance of physiological balance and sustainable realisation of productive potential throughout the growing season. This variant also showed synchronisation of earing and filling, uniformity of plant height and ear maturity, which had a positive effect on grain uniformity and quality during harvesting. An additional factor of agro-ecological sustainability was the ability of plants to compensate for short-term moisture deficits due to increased osmotic activity. In variants B4 and B5, plants retained turgor longer at identical soil moisture, which indicates the influence of biostimulant compounds on the physiological water retention capacity of tissues. It was also noted that such plants moved more slowly into the phase of physiological senescence in the context of of a simultaneous increase in the length of the milk ripeness phase and slower leaf death. Significantly, resistance to weather stress was accompanied not only by an increase in yield, but also by an improvement in its structure: a greater number of productive stems, a higher weight of 1,000 grains, and improved spikelet formation. All this reflects the complex effect of foliar feeding not only on nutrition, but also on the regulation of growth and development under stress. Notably, these effects were achieved without changing the main agronomic practices, which indicates the influence of foliar treatments on physiological processes in critical phases of plant development (Fig. 2).

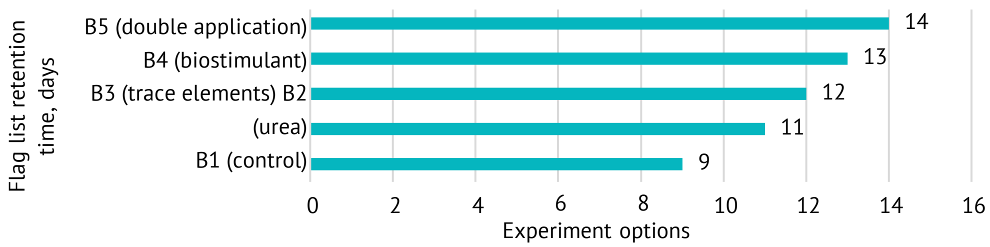

***Figure 2**. Dynamics of flag leaf green mass preservation under temperature and water stress*
***Source:** compiled by the authors*

Thus, foliar nutrition in the weather conditions of Northern Kazakhstan proved to be an effective mechanism for increasing the resistance of wheat to weather fluctuations. Maintaining photosynthetic activity, prolonging the functioning of the leaf apparatus, reducing the rate of ageing and maintaining physiological tone ensured the use of limited resources more efficiently and fulfilled their productive potential. Variant B5, which included early and late fertilisation, ensured the most balanced and sustainable development of the crop, compensating for the impact of short-term climatic stress. This approach can be considered as an adaptive element of intensive wheat cultivation technology in the risky farming zone.

Agronomic and economic efficiency of leaf dressings. In the control variant (B1), where no foliar feeding was applied, the yield was 37.6 c/ha. At the same time, the structure of the crop was characterised by minimal values: the productive density was 383 stems/m^2, the average number of spikelets per ear was 15.4, and the weight of 1,000 grains was 43.4 g. The grain was characterised by a high proportion of small and underdeveloped grains, which reduced its marketability. Gross income was 112,800 t/ha, costs were minimal, but the return on investment remained at zero due to the lack of additional agricultural practices. In the second variant (B2), which included a single foliar treatment with 10% urea solution during the tillering phase, the yield increased to 40.9 c/ha, which corresponded to an increase of 3.3 c/ha or 8.8% compared to the control. The productive density was 394 stems/m^2, the number of spikelets per ear was 15.9, and the weight of 1,000 grains was 44.2 g. The gross income increased to 122,700 tg/ha, the additional costs were 5,000 tg/ha, and the economic effect per hectare was 8,900 tg. The payback ratio was 1.6. Visually, the crops were more evenly developed but reacted sensitively to temperature stress during the tube phase.

The third variant (V3), which included the introduction of a microelement complex in the tube phase, provided a yield of 41.6 c/ha. The increase over the control was 4 c/ha (10.6%), the productive density reached 401 stems/m^2, the number of ears was 16.1, and the weight of 1,000 grains was 44.8 g. The gross income was 124,800 tg/ha, with costs of 6,500 tg/ha; the economic effect reached 7,500 tg/ha. The return on investment was 1.9. Alongside the yield increase, there was better resistance to leaf infections, longer green mass retention and a 13% increase in the proportion of milled grain. The fourth variant (B4) included foliar treatment with a biostimulant based on amino acids and humates during the earing phase. The yield was 42.3 c/ha, which was 4.7 c/ha (12.5%) higher than the control level. The productive density was 405 stems/m^2, the number of ears was 16.3, and the weight of 1,000 grains was 45.1 g. Gross income was 126,900 tg/ha, additional costs were 7,000 tg/ha, and the economic effect was 7,400 tg/ha. The payback ratio reached 1.8. The plants were distinguished by high levels, flag leaf preservation, resistance to overheating and high grain quality at harvest. The share of marketable grain increased by 15%.

The fifth variant (B5), which included two treatments with urea in the tillering phase and a biostimulant in the earing phase, yielded the highest yield of 43.2 c/ha. The increase was 5.6 c/ha or 14.9% compared to the control. The productive density reached 417 stems/m^2, the number of ears was 16.5, and the weight of 1,000 grains was 45.6 g. Gross income increased to 129,600 tg/ha, additional costs amounted to 8,500 tg/ha, and the economic effect reached 18,000 tg/ha. The return on investment was 2.1. There was a 4-5-day extension of the flag leaf viability, minimal disease damage and the lowest proportion of substandard grain (Table 3).

***Table 3**. Productivity and profitability indicators of different foliar feeding schemes*

Variant	Yield, hwt/ha	Productive stems, pcs/ᵐ2	Spikelets per ear, pcs	Weight of 1,000 grains, g	Crop growth, c/ha	Revenue, tonnes per hectare	Additional costs, tonnes/ha	Economic effect, tg/ha	Payback ratio
B1 (control)	37.6	383	15.4	43.4	0	112,800	0	0	0
B2 (urea)	40.9	394	15.9	44.2	3.3	122,700	5.000	8.900	1.6
B3 (trace elements)	41.6	401	161	44.8	4	124,800	6.500	7.500	1.9
B4 (biostimulant)	42.3	405	16.3	45.1	4.7	126,900	7.000	7.400	1.8
B5 (double application)	43.2	417	16.5	45.6	5.6	129,600	8.500	18.000	2.1

***Source:** compiled based on Formula (3)*

In 2023, production experience in areas with low availability of mobile nitrogen and phosphorus was implemented, sowing spring wheat of the Omskaya 36-3 reproduction variety with pre-sowing seed treatment with Scarlet at a rate of 0.4 litres/tonne of seeds. The sown area was 50 hectares. Different doses of phosphate fertiliser in the form of ammophos NP 10-46 were applied at doses of 125 and 95 kg/ha of physical weight according to the approved experimental scheme. Sowing was conducted on 2 June 2024, with a seeding rate of 3 million units/ha or 140 kg/ha. Phenological observations of grain crops were carried out, field germination and weediness of crops were determined, and herbicide treatment with the following preparations was carried out: Phenomenon 0.5 l/ha + Baron 0.015 g/ha + Shansyugen 0.9 l/ha + Title duo 0.3 l/ha + Punto extra 0.025 g/ha. Leaf diagnostics was conducted on wheat leaves, and a deficiency of macro and microelements was identified in the critical phase. For the deficit, leaf treatments were conducted in the phase of entering the tube and the beginning of mowing with nitrogen-phosphorus liquid fertiliser ZhKU 11-37 in different doses on different variants, both with and without pre-sowing application of basic fertilisers. Doses ranging from N1P4 to N13P60 were applied (Table 4).

Table 4*. Spring wheat yield formation in the conditions of southern chornozems of Northern Kazakhstan, depending on different fertilisation systems*

No.	Option name	Green mass, g/m^2 (tube phase)	Ear length, mm	Average number of grains per ear, pcs	Yield, t\ha
2	$N_{13}P_{58}$ (NP calc)	148.5	7.2	29.3	1.16
3	Management	121.5	8.3	32.3	0.75
5	Foliar application of N_2P_7	102.75	7.8	31	0.87
6	Foliar application N_3P_{10}	109	7.5	31.4	0.96
7	Foliar application N_4P_{14}	131	7.7	30.6	0.97
8	($N_{10}P_{41}$) soil application + (N_2P_7) foliar fertilisation	145	8.4	32.9	0.96
9	Soil application $N_{10}P_{41}$	102	8.8	33.78	0.82

Source: *compiled by the authors*

Given the high humidity of 2023, in Lobanovo LLP (Imantau village, Northern Kazakhstan region), foliar feeding without the main fertiliser application did not show its effectiveness compared to the variant with the full calculated dose of N13P58. However, the yield in the control was significantly lower than in the foliar fertilisation variant, at 0.75 t/ha compared to 0.82-1.05 t/ha. Comparing the experiments in different years of moisture, it is possible to conclude that with sufficient moisture, foliar feeding is more effective when applied in combination with the main application of macronutrients (nitrogen and phosphorus).

Thus, in all variants that included foliar feeding, a stable advantage was recorded in terms of yield, the main elements of the productivity structure and economic parameters of crop cultivation. The yield increase ranged from 3.3 to 5.6 c/ha, with the highest increase achieved with two treatments (B5), indicating the effectiveness of the combination of various physiologically active substances and precise phase positioning of fertilisers. The increase in productive density, the number of spikelets per ear and the weight of 1,000 grains in most variants was accompanied by an improvement in the morphophysiological state of plants, a decrease in the phytosanitary load and the prolongation of the functioning of the assimilation apparatus in the critical phases of crop formation. Summarising the data obtained, it can be concluded that the integration of foliar feeding into cereal crop cultivation technology, especially in the form of phased and combined application, is a highly efficient and economically viable element of the adaptive farming system. This approach simultaneously increased the biological realisation of crop potential, reduced dependence on weather stress and improved the economic return on each hectare of sown area.

DISCUSSION

The obtained results demonstrated a significant influence of foliar nutrition schemes on the productivity and physiological state of spring wheat under the weather conditions of Northern Kazakhstan. In the context of the same main dose of fertiliser ($N_{60}P_{40}$), the highest yield was recorded in the variant with double foliar application (B5), which indicates the synergistic effect of the sequential application of urea and biostimulant. Significant changes were also observed in the structure of the crop: an increase in the number of productive stems, weight of 1,000 grains and number of spikelets per ear confirmed the improvement of generative development and efficiency of the photosynthetic apparatus. The increase in the content of chlorophyll and nutrients in the tissues, as well as the growth of the viability index, indicates the activation of metabolic processes and the strengthening of the metabolic stability of plants (Pakhomeev & Ibragimova, 2025). The contribution of foliar nutrition to increasing agro-ecological resistance to abiotic and biotic stresses was particularly significant. Delaying the onset of disease symptoms and preserving the flag leaf during the grain filling phase ensured prolonged photosynthesis, which contributes to the formation of a full-fledged harvest (Drobitko *et al.*, 2024).

In addition, publications by R. Bojović *et al.* (2022) and P. Govindasamy *et al.* (2023) considered aspects of agricultural technology and fertilisers in the context of economic efficiency and climate change. R. Bojović *et al.* studied sugar beet productivity management in Serbia and Montenegro, focusing on the systematic use of mineral fertilisers. However, the study did not cover the issues of plant physiological resistance or the impact of nutrition on the response of crops under stressful conditions. P. Govindasamy *et al.* emphasised the importance of increasing nitrogen use efficiency for sustainable agriculture but limited themselves to conceptual approaches without detailed agronomic adaptation to specific climatic regions. In contrast to these studies, the present study was based on a comprehensive empirical framework with an assessment of physiological, biochemical and economic indicators: a yield increase of up to 15%, a decrease in disease incidence by 11.9 percentage points and an extension of the flag leaf viability were recorded, making it more applicable to the conditions of Northern Kazakhstan.

On the other hand, M. Palka *et al.* (2021) and A. Fast *et al.* (2023) analysed the diagnosis and management of nitrogen nutrition. M. Palka *et al.* confirmed the effectiveness of the CCCI-CNI index for assessing the nitrogen status of wheat but did not consider real agronomic actions to correct nutrition. A. Fast *et al.* conducted field studies on Canadian wheat, establishing productive nitrogen doses with the addition of inhibitors, but did not include foliar treatments and assessment of the physiological response of plants. Compared to these studies, the present study was characterised by a holistic approach: it included field SPAD measurements, visual scoring, disease resistance assessment and comprehensive economic diagnostics. This multi-level methodology ensured not only an increase in yields but also an increase in agro-ecological sustainability without changing the basic agricultural technique (Trembitska & Bohdan, 2023; Kalenska *et al.*, 2025).

Publications by C. Mihuț *et al.* (2022) and F. Mocanu *et al.* (2023) addressed the influence of fertilisers and weather conditions on crop productivity. C. Mihuț *et al.* evaluated different nutrition schemes, but without physiological and phytosanitary indicators, which limited the applied value of the conclusions. F. Mocanu *et al.* determined that drought significantly reduced the productivity of sorghum hybrids but did not propose specific ways to compensate for this effect. This study managed to provide proven solutions, confirming the effectiveness of phase foliar nutrition with biostimulants and microelements. By means of an integrated assessment of physiology, chlorophyll and water retention, pathogen resistance and economics, the adaptive value of the developed schemes in the arid conditions of the region was proved.

F. Chețan *et al.* (2023) and K. Pokovai *et al.* (2025) raised the issues of adaptation of agricultural technology to stressful conditions and rational land use. F. Chețan *et al.* addressed no-till tillage to preserve the structure of chornozems under maize cultivation but did not include agrophysiological parameters of plants. K. Pokovai *et al.* found a decrease in yields under warming conditions but did not evaluate the effectiveness of compensating practices. In contrast to these studies, the present research proved that the use of biostimulants and urea in key phases of wheat organogenesis contributed to the prolongation of the flag leaf function and stabilisation of the photosynthetic apparatus. In addition, under drought conditions, an increase in the proportion of productive stems and an increase in the weight of 1,000 grains were achieved, which directly reflected the crops' resistance to weather stress (Boiko *et al.*, 2024).

The publications by H. Domnariu *et al.* (2025) and K. Akchaya *et al.* (2025) analysed sustainable farming systems, including soil microbiota and the role of legumes in agroecosystems. H. Domnariu *et al.* recorded changes in microbial communities under the influence of different tillage practices, without extending the analysis to plants. K. Akchaya *et al.* summarised the benefits of mixed crops but did not provide quantitative data on the effectiveness of foliar treatments in cereals. In contrast to these approaches, this study was based on field data on foliar nutrition in spring wheat, including trace elements and amino acids. Due to the comprehensive evaluation (SPAD, productivity, disease resistance), the results were highly applicable, which is especially relevant for adaptive agriculture in Northern Kazakhstan.

R. Láposi *et al.* (2024) and M. Mirosavljević *et al.* (2024) studied the physiological responses of maize and the effect of sowing dates on the efficiency of wheat varieties, respectively. R. Láposi *et al.* demonstrated that the use of phytoconditioners increased chlorophyll content in maize during drought, but there was no relationship with yield and pathogen resistance. M. Mirosavljević *et al.* determined differences in nitrogen use among modern varieties but did not consider the effect of foliar treatments. In contrast to these publications, this study combined physiological, agronomic and economic parameters: the optimal fertilisation scheme was determined, which prolonged the functioning of the flag leaf, increasing grain weight and reducing disease incidence.

A. Rahman *et al.* (2023) and J. Behr *et al.* (2024) considered various agrophysiological approaches to improving plant health. J. Behr *et al.* described the effect of long-term use of minimal tillage in combination with moderate doses of nitrogen, which enhanced microbial interactions in the rhizosphere and improved the health of winter wheat. However, productivity and economic efficiency were not analysed. At the same time, A. Rahman *et al.* recorded an increase in flax yield and oil content when phosphorus and zinc were applied in foliar form, but the study did not involve cereals and did not include leaf physiological parameters. In contrast to these limitations, the present study includes not only a detailed analysis of leaf activity by SPAD and flag leaf, but also a comprehensive assessment of yield, disease resistance and profitability, making it applicable to North Kazakhstan conditions.

I. Racz *et al*. (2021) and H. Raniro and J. Santner (2024) conducted a variety of studies on phosphorus uptake by crops in contrasting soil systems. H. Raniro and J. Santner described the differences in phosphorus uptake strategies of cover crops in calcium and decalcified chornozem, but the topic of cereals remained outside the scope of the study. At the same time, I. Racz *et al*. conducted a field assessment of the agronomic properties of spring wheat but did not investigate the effectiveness of foliar nutrition under stressful conditions. This study not only determined the agronomic value of foliar treatments but also recorded their impact on the viability of the leaf apparatus, which is critical in conditions of drought and temperature spikes.

The review by S. Ouda and A. Zohry (2024) and E. Daly *et al*. (2025) addressed climate adaptation and environmental risks. E. Daly *et al*. presented modelling of greenhouse gas emissions under different nitrogen fertilisation regimes, emphasising reducing environmental impact, but did not address plant growth or photosynthesis parameters. S. Ouda and A. Zohry emphasised the agro-ecological benefits of rotating legumes and cereals but omitted the topic of foliar feeding and the physiological response of plants. In contrast, this study demonstrated a clear link between foliar nutrition, disease resistance and photosynthetic activity duration, which has direct agrotechnological applicability. In the context of the presented publications, this study is prominent for its applied orientation and breadth of coverage: it includes agrophysiological, phytopathological and economic aspects. The use of foliar feeding not only increased the yield of spring wheat, but also prolonged the functioning of the flag leaf, improved chlorophyll content, disease resistance and ensured the profitability of the technology in the weather conditions of Northern Kazakhstan.

CONCLUSIONS

During the study, a comprehensive assessment of the effectiveness of different schemes of foliar feeding of durum wheat under the weather conditions of Northern Kazakhstan was conducted. The study determined that foliar nutrition has a complex effect on productivity, physiological condition, disease resistance and adaptive potential of plants under weather stress. Yields increased significantly in all variants compared to the control (37.6 c/ha), reaching 40.9 c/ha with urea (B2), 41.6 c/ha with microelements (B3), 42.3 c/ha with a biostimulant (B4) and a maximum of 43.2 c/ha with two treatments (B5). The increase ranged from 8.8% to 14.9%, depending on the variant. The elements of the yield structure were significantly improved: the number of productive stems increased from 383 pcs/m^2 in the control to 417 pcs/m^2 in the B5 variant, the number of spikelets per ear from 15.4 to 16.5, and the weight of 1,000 grains from 43.4 g to 45.6 g. These changes indicate stimulation of both vegetative and generative development of the crop.

Indicators of physiological condition also showed a significant increase: chlorophyll content in leaves increased from 38.7 to 49.5 SPAD, the content of total nitrogen, phosphorus and potassium in the aboveground mass increased to 3.02%, 0.37% and 1.54%, respectively. The plant viability index increased from 0.74 in the control to 0.89 in the B5 variant, reflecting an improvement in metabolic activity and stress resistance. The fertilisers contributed to a reduction in disease incidence: the area of affected leaves decreased from 26.4% to 14.5%, and the disease index from 3.2 to 1.7 points. There was also a lower incidence of Fusarium infection of ears, at 2.4% against 4.8% in the control. In conditions of heat and moisture deficit (up to +33°C, humidity up to 30-35%), leaf dressing, especially in variants B4 and B5, ensured the preservation of turgor, bright colour and uniform grain filling. The limitation of the study is the conduct of experiments in one agro-ecological region and during one growing season. It is advisable to expand further research to different soil and climatic zones and a multi-year period to assess the stability of the effect of foliar feeding.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Ефективність листових підживлень при комплексному удобренні зернових культур на південних чорноземах Північного Казахстану

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Анотація. Мета дослідження полягала в оцінці впливу листових підживлень на фізіологію, врожайність та економічну ефективність ярої пшениці в Північному Казахстані. Польові випробування були проведені у вегетаційний період 2024 року (травень-серпень) на базі навчально-дослідної ділянки Кокшетауського університету ім. Шокана Уаліханова і були спрямовані на оцінку агроекологічної та економічної ефективності різних схем листових підживлень ярої пшениці. Дослідження включало п'ять варіантів досвіду, що відрізняються складом і кратністю внесення добрив, у тому числі карбаміду, мікроелементів і біостимуляторів. Варіанти з фоліарними обробками демонстрували стійку перевагу за агрофізіологічними показниками, особливо в умовах спекотної та сухої погоди, при температурі близько +33 °C і вологості повітря 30-35 %. Найвищі результати отримано при дворазовому листковому підживленні (варіант B5), де врожайність досягла 43,2 ц/га, що перевищувало контроль на 5,6 ц/га (14,9 %). Маса 1 000 зерен збільшилася до 45,6 г, продуктивна густота – до 417 стебел/м2, а кількість колосків у колосі – до 16,5. Тривалість функціонування прапорцевого листка в цьому варіанті досягала 14 діб, а рівень вмісту хлорофілу залишався високим протягом фази наливу. Відзначалося значне зниження ураження листя іржею (до 14,5 %) і підвищення частки кондиційного зерна на 15 %. Економічний аналіз показав, що варіант B5 забезпечив максимальний дохід (129 600 тг/га) при коефіцієнті окупності 2,1 і економічному ефекті 18 000 тг/га. Решта варіантів забезпечили приріст врожайності від 3,3 до 4,7 ц/га при коефіцієнтах окупності від 1,6 до 1,9. Дані підтверджують доцільність інтеграції фазово підібраних листових підживлень у технології вирощування пшениці в зоні ризикованого землеробства. Порівнюючи досліди в різні роки зволоження, можна зробити висновок, що при достатньому зволоженні, листові підживлення більш ефективні при комплексному внесенні з основним внесенням макроелементів (азоту і фосфору)

Ключові слова: фізіологічна активність; продуктивні стебла; вміст хлорофілу; індекс життєздатності; мікроелементи; яра пшениця; врожайність