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EFFECTS OF FERTILIZER APPLICATION ON WINTER WHEAT GROWTH UNDER HYDRIC STRESS CONDITIONS

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Abstract. *Winter wheat (Triticum aestivum) represents a significant cereal crop in the northeastern region of Romania. Wheat production in this area is frequently constrained by drought stress conditions and low efficiency in the utilization of chemical fertilizers under water deficit scenarios. Consequently, effective water management practices for agricultural productivity in regions experiencing water scarcity necessitate the implementation of innovative and sustainable strategies. In order to evaluate the impact of nitrogen fertilizers and biostimulants on the growth and yield of winter wheat, two experiments were conducted at the Didactic Station of Iași, affiliated with the Iași University of Life Sciences, during the period 2020–2023. The first experiment assessed the sensitivity of winter wheat to the application of five biostimulant fertilizers. The second experiment investigated the response of winter wheat to four slow-release nitrogen fertilizer treatments. The application of biostimulants, particularly Brio N, significantly influences fertilizer efficiency by promoting nutrient uptake through plant roots, enhancing plant tolerance to water stress, and improving the plant's ability to metabolize essential nutrients. Additionally, the use of nitrogen-based foliar fertilizers such as N3 positively impacts plants experiencing hydric stress. Specifically, it enhances the plants' tolerance to water scarcity, boosts photosynthetic activity, and supports protein synthesis. Furthermore, soil-applied liquid nitrogen fertilizers, represented by N1 and N2, have shown beneficial effects on yield parameters, enhancing overall plant growth, improving crop quality, and increasing yield-quality parameters. These fertilizers ensure that nitrogen is immediately accessible to plants and generate a notable "stay-green" effect, prolonging the functional lifespan of chloroplasts. Lastly, the use of controlled-release nitrogen fertilizers like Sulfammo 25 and Sulfammo 30 also contributes substantially to improved plant growth and crop quality. These fertilizers gradually release nitrogen throughout the vegetation period, increasing nitrogen utilization efficiency and further extending the chloroplasts' lifespan through the "stay-green" effect.*

Keywords*: biostimulant fertilizers, chemical fertilizers, nitrogen slow-release, winter wheat.*

INTRODUCTION

In northeastern Romania, one of the main challenges faced by farmers is the increasing frequency of hydric stress, which directly affects crop productivity and the efficiency of resource use. Winter wheat (*Triticum aestivum L.*), a staple crop in this region, is particularly sensitive to drought, especially during critical phenological stages, resulting in significant yield reductions (Ahmad et al., 2024; Yang et al., 2024).

Under water-deficit conditions, fertilization efficiency—especially nitrogen—is severely impaired. Low soil moisture limits the dissolution and mobility of nutrients, reducing their availability to plants. Additionally, hydric stress disrupts root system function and interferes with the metabolic processes involved in nutrient uptake (Kaur et al., 2024; Dinu & Rusu, 2023; Bărbulescu & Stanciu, 2023).

Nitrogen, essential for protein synthesis, root development, and photosynthesis, plays a critical role in the plant's response to abiotic stress (Agami, 2022). Studies have shown that rational nitrogen application can maintain key physiological traits under drought and heat conditions, such as chlorophyll content, nitrogen remobilization, and antioxidant activity (Chen et al., 2024; Li X. et al., 2024; Lv et al., 2021). Furthermore, nitrogen fertilization has been

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shown to mitigate the combined effects of drought and heat stress by enhancing photosynthetic efficiency and overall stress tolerance (Li M. et al., 2024).

Modern research emphasizes the use of nitrogen formulations adapted to stress conditions, such as controlled-release fertilizers, which provide a constant supply of nitrogen and minimize losses through leaching and volatilization (Zhang et al., 2023; Ikeda et al., 2014). Foliar nitrogen-based biostimulants have also proven effective in triggering physiological responses, including the "stay-green" effect, by extending chloroplast functionality under stress (Lucini et al., 2024; Rouphael & Colla, 2020).

This research aims to identify sustainable agronomic solutions based on rational nitrogen use that can enhance the resilience of winter wheat under increasingly unstable climatic conditions in drought-affected regions.

MATERIAL AND METHODS

The experiment was conducted in 2022 at the Didactic Station of the University of Life Sciences "Ion Ionescu de la Brad" in Iași, Ezăreni Farm (47°07' N, 27°30' E). The study aimed to evaluate the impact of solid fertilizers and foliar biostimulants on winter wheat development and yield under hydric stress.

The research focused on identifying efficient fertilization strategies for drought conditions, emphasizing water and nutrient management, macronutrient roles (N, P, K), and the use of controlled-release fertilizers and biostimulants. Several innovative products were assessed, including nitrogen-based foliar fertilizers (FR Foliar), stabilized liquid fertilizers (Excelis Power, Excelis Green), and slow-release formulations (Sulfammo 25, 30).

The experimental site was located on cambic chernozem soil in the Moldavian Plain, characterized by a loam-clay texture and moderate to high fertility. A randomized block design with four replications was employed, testing eight fertilization variants across 42 m² microplots (Table 1).

Table 1

Experimental treatments and nitrogen application rates by growth stage

T	Sowing (kg/ha)	Tillering (BBCH 0-25) (kg/ha)	1st Node (BBCH 31) (kg/ha)	Flag Leaf Stage (BBCH 49) (kg/ha)	S	T	1-st	Flag	Total N
1	NP 20-20-0 (200)	AN (150)	AN (150)	-	40	49,5	49,5	0	139
2	NP 20-20-0 (200)	**Sulfammo 30** (130)	AN (150)	-	40	39	49,5	0	128,5
3	NP 20-20-0 (200)	AN (150)	**N 2 liquid** (150) HU Excelis Green	-	40	49,5	36	0	125,5
4	NP 20-20-0 (200)	**N 1 liquid** (150) HU Excelis Power	AN (150)	-	40	33	49,5	0	122,5
5	NP 20-20-0 (100)_	Ureea (120)	AN (100)	**Brio N** (20)	20	55,2	33	5,7	113,9
6	NP 20-20-0 (100)	Ureea (120)	AN (100)	**N3 foliar** FR- Foliar (30)	20	55,2	33	5,7	113,9
7	NP 20-20-0 (100)	Ureea (120)	**N2 liquid** (100) HU Excelis Green	**N3 foliar** FR- Foliar (30)	20	55,2	24	5,7	104,9
8	NP 20-20-0 (100)	Ureea (120)	**Sulfammo 25** (100)	**N3 foliar** FR- Foliar (30)	20	55,2	25	5,7	105,9

Fertilization was applied at four phenological stages, following the BBCH scale: sowing (BBCH 0–10), tillering (BBCH 25–31), first node (BBCH 31), and flag leaf (BBCH 49). Treatments differed in nitrogen dose and type, including slow-release (Sulfammo 25, 30), stabilized liquid forms (Excelis Power, Excelis Green), and foliar biostimulants (Brio N, N3 foliar) (Table 1). The fertilizers varied in chemical composition, formulation, and application method. Table 2 summarizes the key characteristics of the products tested.

Table 2

Chemical and technological characteristics of applied fertilizers

Fertilizer	Nitrogen (%)	Key Components	Type	Additional Notes
NP 20-20-0	20	20% P	Solid	Starter fertilizer for sowing
AN 34	34	17% NH_4, 17% NO_3	Solid	Fast nitrogen availability, prone to leaching
Urea 46	46	$CO(NH_2)_2$	Solid	Requires hydrolysis; efficiency improved with NBPT
Sulfammo 25	25	18% NH_4, 7% NO_3, 2% MgO, 31% SO_3	Solid (slow-release)	MPPA DUO, plant extract XCK
Sulfammo 30	30	5% NH_4, 25% Urea, 3% MgO, 15% SO_3, 0.15% B, 0.10% Zn	Solid (slow-release)	Organocalcium matrix, N-PRO enzyme activator
N1 – Excelis Power	33	NBPT, DCD, Rhizovit®, 3% MgO, 15% SO_3	Liquid (stabilized)	Enhances root growth and nitrogen use efficiency
N2 – Excelis Green	24	NBPT, DCD, Rhizovit®, 3% MgO, 15% SO_3	Liquid (stabilized)	Sustained nitrogen release and stay-green effect
N3 Foliar (FR-Foliar)	19	19% N, 2% MgO, 0.10% Zn	Liquid (foliar)	Enhances photosynthesis and nutrient redistribution
Brio N	28.5	Seaweed extracts, N-PRO	Liquid (biostimulant)	Improves nutrient uptake, stress tolerance

Winter wheat (Izvor C1 variety, 250 kg/ha) was sown on November 2, following maize as a preceding crop. Soil was prepared using minimum tillage, including scarification and seedbed preparation in late October. Basal fertilization was applied before sowing.

Weed control was performed in two phases using Dicopur 464 SL (BBCH 30–31) and Tomigan 250 EC (BBCH 49–50). On May 15, plant protection treatments included Bumper 250 EC (fungicide) and Decis 25 WG (insecticide). Harvesting was conducted on July 18 using a Wintersteiger Classic plot combine equipped with the GrainGage system for accurate yield, moisture, and test weight measurement.

Soil was analyzed according to ICPA Bucharest standards, assessing pH, total nitrogen, available P and K, $CaCO_3$, humus, and trace elements. Yield components (grain weight, moisture, test weight) were determined using the GrainGage HM800 system, and thousand kernel weight (TKW) was assessed per SR 6123/1999.

Physiological measurements included chlorophyll content (CCM-200 Plus) and stomatal conductance (SC-1 porometer), indicators of plant response to fertilization and drought. Data were analyzed using one-way ANOVA (Microsoft Excel), with treatment differences evaluated via Duncan's test ($p \leq 0.05$).

RESULTS AND DISCUSSIONS

1. Soil chemical properties

The soil assessment (0–20 cm layer) revealed conditions moderately favorable for wheat development under drought. The pH was slightly acidic (6.58), favoring nutrient availability. Phosphorus levels were moderate (20.9 ppm), potassium was abundant (248.4 ppm), and humus content was medium (2.99%), supporting nutrient retention and mineralization. The exchangeable base content was high (EB = 29.5 me%), with a base saturation of 89.8% and low hydrolytic acidity (Ah = 2.29 me%). The nitrogen index (IN = 2.56) indicated a moderate to high potential for nitrogen mineralization.

Table 3

Soil Chemical Properties

Depth (cm)	pH	P (ppm)	K (ppm)	Humus (%)	EB (me%)	Ah (me%)	SB (%)	Carbonates	I.N.
0–20	6.58	20.9	248.4	2.99	29.5	2.29	89.8	-	2.56

2. Climatic analysis

The 2021–2022 season was characterized by climatic variability that significantly affected wheat development under hydric stress. Autumn 2021 was extremely dry, with rainfall well below normal (1.2 mm in August and 3.4 mm in October), likely limiting germination and early root development. Winter remained cold and relatively dry, but with slightly warmer-than-average temperatures. Spring brought favorable conditions, with substantial rainfall—especially in May (125.2 mm, +69.8 mm)—and elevated temperatures that promoted vegetative growth. In contrast, July was marked by renewed drought (24.2 mm, −46.5 mm), coinciding with grain filling and potentially reducing final yields. The sequence of dry autumn, mild winter, wet spring, and dry summer strongly influenced nutrient dynamics and crop performance.

3. Shoot development and productive tiller formation

The number of shoots per square meter is a key indicator of vegetative vigor and yield potential in winter wheat, with nitrogen availability being a major influencing factor. In this study, all variants were sown at the same density (580 seeds/m²), ensuring uniform emergence. Significant differences were observed during early tillering (BBCH 21–23), with shoot counts ranging from 440 in the unfertilized control to 522 in T4 (NP 20-20-0/N1 liquid/AN).

Statistical analysis ($F = 16.52$, $p < 0.001$) confirmed that treatments with stabilized or slow-release nitrogen (T2–T4) significantly enhanced shoot formation. Duncan's test identified T3 and T4 as top-performing variants, indicating the positive impact of nitrogen stabilization on early vegetative development under hydric stress.

By stem elongation (BBCH 35–40), differences among treatments diminished ($p = 0.604$), likely due to inter-plant competition and environmental factors. However, higher shoot numbers persisted in T3 (545) and T6 (543), suggesting sustained physiological benefits from foliar N3.

Table 3

Shoot Development and Productive Tiller Formation

Treatments	Seeds/mp (sowing)	No. shoots /mp (BBCH 21-23)	No. shoots/mp (BBCH 35-40)	No ears/mp (Harvest)
Non fertilised	580	440[f]	498[a]	474[a]
T1 - 20-20-0/AN/AN	580	499[bc]	521[a]	498[a]
T2 - 20-20-0/Sulfamo 30/AN	580	510[abc]	526[a]	503[a]
T3 - 20-20-0/AN /N 2 liquid	580	520[ab]	545[a]	526[a]
T4 - 20-20-0/N 1 liquid/AN	580	522[a]	522[a]	500[a]
T5 - 20-20-0/Ureea/AN + Brio N	580	472[de]	539[a]	520[a]
T6 - 20-20-0/Ureea/AN + N3 foliar	580	476[d]	543[a]	519[a]
T7 - 20-20-0/Ureea/N 2 liquid + N3 foliar	580	452[ef]	532[a]	520[a]
T8 - 20-20-0/Ureea/Sulfamo 25 + N3 foliar	580	493[cd]	530[a]	505[a]
F-value (ANOVA)		*16,52*	*0,80*	*1,16*
p-value		*<0,001*	*0,604*	*0,341*

Note: Means followed by the same letter are not significantly different, while different letters indicate significant differences according to Duncan's multiple range test ($p < 0.05$).

At harvest, ear number differences were not statistically significant ($p = 0.341$), yet variants T5–T7 maintained higher values (519–520 ears/m²), reflecting improved tiller survival with biostimulant-enhanced nutrition. The control remained lowest (474), confirming the detrimental impact of nutrient limitation.

Overall, the data highlight that nitrogen strategy—particularly involving stabilized and foliar forms—supports tiller formation and productivity, contributing to higher yield potential under water-limited conditions.

4. Water stress indicators

Chlorophyll content, measured at BBCH 31 and BBCH 65, proved to be a sensitive indicator of photosynthetic activity under water-limited conditions. ANOVA revealed significant treatment effects at both stages ($F = 12.87$ and 23.44; $p < 0.001$), with Duncan's test distinguishing the control as statistically inferior (CCI = 24.6 and 25.9).

Highest CCI values were observed in T6 (34.9), T5 (34.6), T3 (33.8), T7 and T8 (33.7), reflecting enhanced chloroplast activity and delayed senescence. These effects are characteristic of the "stay-green" response facilitated by foliar biostimulants and stabilized nitrogen (Lucini et al., 2024; Rouphael & Colla, 2020). In contrast, T1 and T2, which lacked biostimulants, showed intermediate CCI levels.

Stomatal conductance, evaluated at the same stages, showed no statistically significant variation among treatments ($F = 1.11$ and 0.58; $p > 0.05$). Despite the lack of significance, physiological patterns were evident. At BBCH 31, T3 and T1 (≈299 mmol m^{-2} s^{-1}) showed the highest conductance, suggesting active gas exchange under stabilized nitrogen and ammonium nitrate inputs. At flowering, treatments with foliar N3 (T5–T8) maintained higher conductance (>225), implying better water regulation. These trends align with Waraich et al. (2011) and Kaur & Sharma (2024), supporting the hypothesis that optimized nitrogen strategies combined with biostimulants contribute to improved stomatal function and drought resilience.

Table 4

Water Stress Indicators

Treatments	**Clorophyl content** (CCI)		**Stomatal conductance** (mmol m-2 s-1)	
	At 2 nodes	Flowering	At 2 nodes	Flowering
Non fertilised	24,6[c]	25,9[c]	224,1[a]	176,8[a]
T1 - 20-20-0/AN/AN	32,0[ab]	33,4[a]	298,8[a]	221,8[a]
T2 - 20-20-0/Sulfamo 30/AN	30,0[b]	31,2[b]	265,0[a]	217,9[a]
T3 - 20-20-0/AN /N 2 liquid	31,5[ab]	33,8[a]	298,9[a]	218,8[a]
T4 - 20-20-0/N 1 liquid/AN	31,2[ab]	33,7[a]	226,2[a]	203,4[a]
T5 - 20-20-0/Ureea/AN + Brio N	33,0[a]	34,6[a]	260,7[a]	233,0[a]
T6 - 20-20-0/Ureea/AN + N3 foliar	32,7[a]	34,9[a]	250,0[a]	225,8[a]
T7 - 20-20-0/Ureea/N 2 liquid + N3 foliar	32,4[a]	33,7[a]	227,4[a]	227,2[a]
T8 - 20-20-0/Ureea/Sulfamo 25 + N3 foliar	30,0[b]	33,7[a]	243,8[a]	232,1[a]
F-value (ANOVA)	12,87	23,44	1,11	0,58
p-value	*<0,001*	*<0,001*	0,387	0,783

Note: Means followed by the same letter are not significantly different, while different letters indicate significant differences according to Duncan's multiple range test (p < 0.05).

6. Grain protein and gluten content

Grain protein and gluten levels are essential quality traits in wheat, particularly sensitive to nitrogen availability under hydric stress. ANOVA confirmed significant differences between treatments ($p < 0.001$), indicating the decisive role of nitrogen form and application strategy in protein accumulation.

The highest protein content was recorded in T3 (15.1%) and T8 (15.0%), followed by T2 and T7 (14.9%), forming the top statistical groups (a–ab). These treatments combined

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stabilized (N2 liquid) or slow-release nitrogen (Sulfammo 25/30) with foliar biostimulants (N3), suggesting a synergistic effect on protein biosynthesis. The control (14.2%) had the lowest protein level and differed significantly from all fertilized variants.

A similar trend was noted for gluten content. T3 and T8 again led with 30.1% and 30.0%, while T4 and T6 (28.3%), lacking foliar biostimulants, showed significantly lower values. The control variant, although intermediate (28.8%), remained statistically inferior to the best-performing treatments.

These results are consistent with Chen et al. (2024) and Li et al. (2024), who reported that combining optimized nitrogen forms with foliar stimulants improves grain quality under drought. The marked increase in protein and gluten content under enhanced treatments confirms the role of nitrogen efficiency in quality expression during stress.

Table 5

Grain Protein and Gluten Content

Treatments	Protein (%)	Gluten (%)
Non fertilised	14,2[e]	28,8[cd]
T1 - 20-20-0/AN/AN	14,5[cd]	28,8b[cd]
T2 - 20-20-0/Sulfamo 30/AN	14,9[abc]	29,6[ab]
T3 - 20-20-0/AN /N 2 liquid	15,1[a]	30,1[a]
T4 - 20-20-0/N 1 liquid/AN	14,6[bcd]	28,3[cd]
T5 - 20-20-0/Ureea/AN + Brio N	14,6[bcd]	29,2b[cd]
T6 - 20-20-0/Ureea/AN + N3 foliar	14,4[de]	28,3[cd]
T7 - 20-20-0/Ureea/N 2 liquid + N3 foliar	14,9[ab]	29,9[ab]
T8 - 20-20-0/Ureea/Sulfamo 25 + N3 foliar	15,0[a]	30,0[ab]
F-value (ANOVA)	*7,24*	*5,95*
p-value	*<0,001*	*<0,001*

Note: Means followed by the same letter are not significantly different, while different letters indicate significant differences according to Duncan's multiple range test (p < 0.05).

7. Yield parameters and grain quality

Significant yield differences among treatments (p < 0.001) confirmed the strong influence of fertilization under hydric stress. The control (3.37 t/ha) produced the lowest yield, while T3 (20-20-0 / AN / N2 liquid) reached the highest value (5.29 t/ha), followed closely by T2, T5, T6, and T8 (>5 t/ha). These variants combined ammonium nitrate with stabilized nitrogen (N2 liquid) and/or biostimulants, enhancing nitrogen availability during drought-sensitive phases and improving crop performance.

Grain moisture content was uniform across treatments (10.0–10.6%; p = 0.538), indicating similar physiological maturity. Test weight (HW), ranging from 72.9 to 77.1 kg/hl, showed no significant differences (p = 0.198); the higher value in the control likely reflects a compensatory effect due to lower grain number.

Thousand grain weight (TGW) varied significantly (p < 0.001), with T3 (16.0 g), T5 (15.8 g), and T8 (15.6 g) achieving the highest values. These treatments, involving biostimulants and slow-release fertilizers, likely supported grain filling through enhanced photosynthetic efficiency and nutrient remobilization (Chen et al., 2024; Li et al., 2024).

In conclusion, optimized nitrogen strategies and biostimulant use not only improve yield under drought but also positively affect grain weight, while having minimal influence on harvest moisture and test weight.

Table 6

Yield Parameters and Grain Quality

Treatments	**Yield (to/ha)**	**Moisture (W%)**	**HW (kg/hl)**	**TGW (g)**
Non fertilised	3,37d	10,3[a]	77,1[a]	14,6b
T1 - 20-20-0/AN/AN	5,05b	10,6[a]	75,0[a]	15,6ab
T2 - 20-20-0/Sulfamo 30/AN	5,08b	10,4[a]	72,9[a]	15,5a
T3 - 20-20-0/AN /N 2 liquid	5,29a	10,3[a]	74,0[a]	16,0a
T4 - 20-20-0/N 1 liquid/AN	4,74c	10,5[a]	75,0[a]	14,9b
T5 - 20-20-0/Ureea/AN + Brio N	4,99b	10,2[a]	75,7[a]	15,8a
T6 - 20-20-0/Ureea/AN + N3 foliar	5,04b	10,5[a]	74,0[a]	15,0b
T7 - 20-20-0/Ureea/N 2 liquid + N3 foliar	4,81c	10,6[a]	74,5[a]	14,6b
T8 - 20-20-0/Ureea/Sulfamo 25 + N3 foliar	5,02b	10,0[a]	74,1[a]	15,6a
F-value (ANOVA)	88,67	0,89	1,56	9,36
p-value	<0,001	0,538	0,198	<0,001

Note: Means followed by the same letter are not significantly different, while different letters indicate significant differences according to Duncan's multiple range test ($p < 0.05$).

8.Correlations between physiological indicators and productivity

8.1 Yield vs. chlorophyll content

A strong positive correlation was observed between grain yield and chlorophyll content (CCI), particularly at flowering (BBCH 65), underscoring CCI as a key physiological indicator under drought conditions. Variants T3 and T5, which integrated stabilized nitrogen or foliar biostimulants, recorded the highest CCI values (33.8 and 34.6) and yields (5.29 and 4.99 t/ha, respectively), highlighting the role of chlorophyll retention in yield formation.

Conversely, the control showed both the lowest CCI (25.9) and yield (3.37 t/ha), confirming the detrimental effects of nitrogen deficiency on photosynthetic activity and assimilate production. The alignment of CCI and yield across treatments validates the use of chlorophyll content as a predictive, non-invasive parameter for assessing fertilization efficiency under water stress.

These findings are consistent with studies by Lucini et al. (2024) and Rouphael & Colla (2020), who reported that biostimulants and controlled-release nitrogen enhance chlorophyll persistence and grain filling under suboptimal water availability.

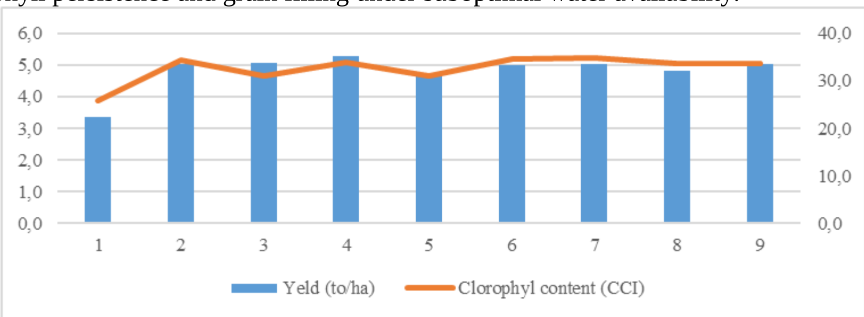

Figure 1. Correlations between yield and chlorophyll content

8.2 Protein content (%) vs. total nitrogen applied and chlorophyll content

Grain protein content exhibited a clear positive relationship with both the total nitrogen applied and the chlorophyll content at flowering. Treatments receiving higher nitrogen doses and featuring stabilized or foliar formulations (T3, T7, T8) recorded the highest protein levels (≥14.9%), indicating that both the quantity and form of nitrogen directly influence protein biosynthesis.

or instance, T3, which included N2 liquid at the stem elongation stage, achieved the highest protein concentration (15.1%) and one of the highest CCI values (33.8), reflecting efficient nitrogen uptake and assimilation. Similarly, T8 (Sulfammo 25 + N3 foliar) combined slow nitrogen release with foliar stimulation, resulting in 15.0% protein and high chlorophyll retention. These data suggest a synergistic effect where prolonged photosynthetic activity—indicated by high CCI—supports nitrogen assimilation into protein compounds during grain filling.

In contrast, the unfertilized control, with minimal nitrogen input and the lowest CCI (25.9), also showed the lowest protein content (14.2%). This reinforces the dual role of nitrogen and photosynthetic capacity in determining grain quality under stress.

These results align with previous findings by Chen et al. (2024) and Li et al. (2024), confirming that integrated nitrogen management enhances both physiological activity and grain protein accumulation, especially under limited water availability.

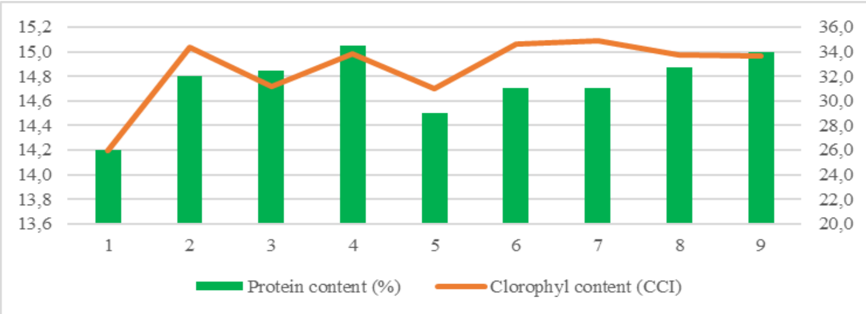

Figure 2. Correlations between protein content (%) vs. Total nitrogen applied and chlorophyll content

8.3 Yield vs. shoots per m²

The number of shoots per square meter is a critical agronomic indicator of early crop vigor and its potential for yield formation. In this study, a positive correlation was observed between shoot density at BBCH 35–40 and the final grain yield, confirming that treatments which stimulated vegetative growth early in the season also led to higher productivity at harvest.

Variants T3 and T6, for instance, recorded high shoot counts (545 and 543 shoots/m², respectively) and correspondingly high yields (5.29 and 5.04 t/ha). These treatments included combinations of ammonium nitrate, N2 liquid, and N3 foliar, suggesting that the synergy between mineral nitrogen and foliar biostimulants promotes not only shoot emergence but also shoot survival and conversion into productive ears.

Conversely, the unfertilized control showed the lowest number of shoots (498/m²) and the lowest yield (3.37 t/ha), further reinforcing the contribution of fertilization to tiller development and final yield. Although the statistical analysis showed that differences in shoot numbers were not significant at all growth stages, the physiological and productive outcomes indicate that early tiller stimulation is a reliable predictor of yield under drought conditions.

The results align with previous findings by Fageria et al. (2014), who emphasized that nitrogen enhances tillering and ear formation, especially under suboptimal water conditions. Thus, the positive relationship between shoot density and grain yield highlights the importance of fertilization timing and formulation in building productive canopy architecture.

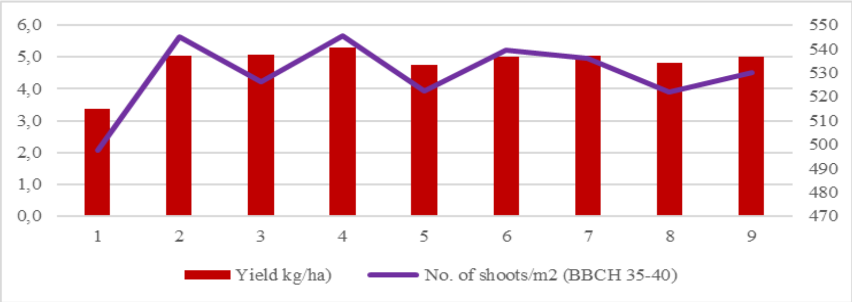

Figure 3. Correlations between yield vs. Shoots per m²

CONCLUSIONS

1. Fertilization strategy plays a key role in enhancing winter wheat development, physiological stability, and yield under hydric stress conditions. Combinations of base fertilizers with slow-release nitrogen and foliar biostimulants yielded the most consistent results.

2. Chlorophyll content at flowering proved to be a reliable physiological indicator, positively correlating with grain yield. Treatments that maintained higher CCI values also achieved superior productivity, confirming the importance of sustained photosynthesis in drought adaptation.

3. Stomatal conductance varied less significantly but showed physiological trends linked to improved water use efficiency. Treatments with stabilized nitrogen promoted better stomatal regulation, supporting photosynthetic stability during stress.

4. Shoot density at BBCH 35–40 was positively correlated with final yield, demonstrating that fertilization strategies supporting early tillering contribute directly to productive spike 5 formation.

5. Grain protein content was enhanced by both the total nitrogen applied and photosynthetic activity. The best protein results were obtained in treatments combining stabilized nitrogen (e.g., N2 liquid, Sulfammo 25) with foliar support (N3 foliar), highlighting improved nitrogen assimilation and remobilization.

6. The most effective treatments were:

T3 (AN + N2 liquid): highest yield and protein content.

T5 (Urea + AN + Brio N): strong shoot development and chlorophyll persistence.

T8 (Urea + Sulfammo 25 + N3 foliar): enhanced grain quality (protein and gluten).

T6 (Urea + AN + N3 foliar): physiological stability and balanced yield.

7. Integrated fertilization schemes—using solid NP base, stabilized nitrogen, and foliar biostimulants—were superior to conventional nitrogen strategies alone. These combinations enhanced nitrogen use efficiency, physiological resilience, and grain quality under drought.

8. The results provide a scientific basis for improving wheat fertilization in semi-arid environments, supporting both yield sustainability and environmental efficiency through more precise nutrient management.

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