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DYNAMICS OF SOLUBLE CARBOHYDRATES IN WINTER WHEAT UNDER IRRIGATED AND RAINFED CONDITIONS: GENETIC POTENTIAL AND ENVIRONMENTAL FACTORS

M. NEGBOYEVA^{1*}, A. SANAKULOV¹, S. VALIYEV¹, D. MANSUROV¹,
 M. MAKHRAMOVA¹, and R. NURALIEVA²

¹Samarkand State University named after Sharof Rashidov, University Boulevard, Samarkand, Uzbekistan

²Samarkand State Medical University, Samarkand, Uzbekistan

*Corresponding author's email: negboyevamaftuna@gmail.com

Email addresses of co-authors: sanakulov1975@gmail.com, shuhratvaliyev7@gmail.com, dierbekmansurov27@gmail.com, maxramovamarhabo@gmail.com, rano_nuralieva@mail.ru

SUMMARY

This study aimed to evaluate the carbohydrate dynamics at the tillering nodes of four winter wheat (*Triticum aestivum* L.) cultivars (Antonina, Yaksart, Moskvich, and Ilgor) under irrigated and rainfed conditions in the semi-arid Nurobod District, Uzbekistan. Soluble sugar quantification used the HPLC (high-performance liquid chromatography) during the wintering period (December-March). The two-way analysis of variance revealed the cultivars (Factor A) were the dominant driver of total variance in sugar variation (74.5%–76.8%) in January, while the growing conditions (Factor B) approximately contributed 10% ($P \leq 0.001$). A significant negative correlation ($r = -0.84$) between the soil moisture and total sugar content disclosed the robust osmotic adaptation under rainfed stress conditions. Among the wheat genotypes, locally adapted cultivars Yaksart and Ilgor exhibited the highest sugar retention and stability. The results suggested that while environmental stress factors trigger the sugar synthesis, the magnitude of the cryoprotective response was primarily the genotype genetic trait, proving cultivars Yaksart and Ilgor as highly resilient for dryland farming.

Keywords: Winter wheat (*T. aestivum* L.), climate-resilient cultivars, crown tissue, genotype-environment interaction, HPLC, rainfed stress conditions, soluble carbohydrates

Key findings: The results revealed the genotype genetic potential was the primary driver of sugar accumulation in winter wheat (*T. aestivum* L.). The significant negative correlation between soil moisture and sugar content confirmed the robust osmotic adaptation mechanism under rainfed stress. Cultivars Yaksart and Ilgor were distinctly with the highest carbohydrate stability and retention, proving them the most climate-resilient cultivars.

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INTRODUCTION

In the present era, the intensification of global climate change and increasing water scarcity have posed significant challenges to crop productivity, particularly under rainfed (dryland) farming systems. In semi-arid regions, such as Uzbekistan, drought stress has become a primary limiting factor in cereal production and quality, necessitating the selection of stress-tolerant crop cultivars, a critical priority for ensuring food security. Therefore, for sustainable agriculture in these vulnerable areas, the knowledge based on the physiological and biochemical mechanisms of crop plant adaptation under varying water regimes is crucial (Usmanova *et al.*, 2025; Ergashev *et al.*, 2025).

In general, moisture plays a pivotal role in the organism's life and further growth and development. Identifying the physiological parameters that determine the resistance of crop plants to water deficit conditions is the most important task, the solution of which has considerable theoretical and practical significance. Dehydration disrupts the vital parameters, such as viscosity and permeability of the protoplasm, the degree of hydration of its colloids, and the pH level of the system. This inevitably leads to fundamental variations in the state and function of the cell's enzyme systems (Makhramova *et al.*, 2025).

Winter wheat (*Triticum aestivum* L.) survival and productivity under rainfed environments primarily depend on the plants' ability to withstand low temperatures and moisture deficit conditions during the wintering period. Carbohydrate metabolism plays a decisive role in this cold-hardening process. However, this journey begins with the mobilization of seed reserves; during the early stages of growth, starch hydrolysis occurs in the endosperm by the α - and β -amylase enzymes into dextrin, and subsequently into monosaccharides, such as glucose and maltose, providing the primary energy source for the developing seedling (Hopkins and Hüner, 2009; Taiz *et al.*, 2022).

As autumn progresses and temperatures drop, a metabolic shift occurs in various tissues of winter wheat. Starch, the

main storage carbohydrate, undergoes enzymatic cleaving by amylases, invertase, and saccharase into soluble sugars, primarily monosaccharides (glucose and fructose) and disaccharides (sucrose) (Taiz *et al.*, 2018; Renata, 2020). These soluble carbohydrates act as crucial cryoprotectants within cells of tillering nodes and act as the vital organ for plant survival and regrowth and development in spring. By increasing osmotic pressure, binding intracellular water, and stabilizing colloidal state of the protoplasm, these sugars prevent lethal ice crystal formation and stabilize membrane structures under environmental stress conditions (Zakharova and Zakharov, 2019).

Furthermore, during late autumn, photosynthates (assimilates) reached translocation via the phloem to the tillering nodes and conversion into sucrose by enzymes like sucrose-phosphate synthase (Ehdaie and Waines, 2001). Sucrose serves as the primary storage carbohydrate, maintaining metabolic activity during the dormant winter phase. Under decreasing temperature conditions, starch synthesis is restricted, while the concentration of osmotically active sugars, such as glucose, fructose, and especially sucrose, gains significant enhancement to lower the freezing point of the cellular sap (Pollock and Cairns, 1991; Livingston and Henson, 1998).

The tillering node acts as a reservoir of energy resources, and its sugar content is the direct indicator of winter hardiness. In well-developed winter wheat, sugar levels can reach up to 40% by December, though these reserves entail gradual consumption throughout the winter, typically decreasing by 2% every 10 days, depending on thermal fluctuations (Sasaki and Kawakami, 2009).

Despite the wealth of general knowledge on wheat physiology, only limited data prevails on the specific carbohydrate dynamics of modern wheat cultivars like Antonina, Yaksart, Moskvich, and Ilgor under the unique semi-arid conditions of the Samarkand Region, Uzbekistan. Therefore, this study aimed to evaluate how different agro-ecological conditions (irrigated vs. rainfed) influence the sugar profile in tillering nodes of

these promising wheat (*T. aestivum* L.) cultivars and to provide a scientific basis for selecting the most climate-resilient genotypes for dryland farming.

MATERIALS AND METHODS

Study site and environmental conditions

The field experiments on winter wheat (*T. aestivum* L.) took place during the 2024–2025 growing season at the 'Ozodjon Obidjon Orif Farm,' located in the Nurobod District, Samarkand Region, Uzbekistan (39.4440°N, 66.2432°E). The said region had characteristics of a semi-arid climate with an average annual precipitation of 250–350 mm, predominantly occurring during winter and spring. The experimental design included two contrasting agroecological conditions, viz., a) irrigated (control), with the wheat fields receiving water supply to maintain optimal soil moisture, and b) rainfed (dry farming/Lalmi), in which wheat fields were entirely dependent on natural precipitation, representing a water-stressed environment.

Soil characterization

The soil of the experimental plots received a classification of light-colored gray soil (Calcixerosols). Before executing the experiments, soil physical and chemical properties sustained analysis at two depths (0–30 and 30–50 cm) (Gulyaev and Ermakov, 1989; Ismatova and Ismoilova, 2022). Size distribution of soil particles entailed determination using the Kachinsky pipette method. Both irrigated and dryland soils were under the medium loam category, with a physical clay fraction (< 0.01 mm) ranging from 31.7% to 35.4% (Table 1). The measurement of total humus content employed the Tyurin method (dichromate oxidation). The initial humus levels were low (0.36%–0.54%). Total nitrogen (N), phosphorus (P), and exchangeable potassium (K) quantifications used standard agrochemical protocols (Table 2).

Plant materials and experimental design

Four winter wheat (*T. aestivum* L.) cultivars (Antonina, Yaksart, Moskvich, and Ilgor) adapted to local environmental conditions were selected specimens for the study. The seeds entailed sowing in October with a seeding rate of 4.5 million germinating seeds per hectare. Each subplot size was 50 m², arranged in a randomized complete block design (RCBD) with four replications (Kumakov, 1985; Kuznetsov and Dmitrieva, 2001).

Carbohydrate analysis

The concentration of soluble carbohydrates (monosaccharides, disaccharides, and total sugars) in tillering nodes of winter wheat seedlings succeeded in its determination using the high-performance liquid chromatography (HPLC), as per the international standard GOST 31669-2012 (Nazarenko *et al.*, 2014). Plant samples (tillering nodes), collected on December 20, January 20, and March 20, received immediate cleaning of soil before freezing, then drying to a constant weight. Carbohydrate extraction from the dry matter used 80% aqueous ethanol. The identification and quantification of individual sugars (glucose, fructose, and sucrose) proceeded using a liquid chromatograph equipped with a refractive index detector (RID). The results gained expression in milligrams per gram (mg/g) of dry weight (DW). Total sugar content calculation was the sum of monosaccharides and disaccharides.

Statistical analysis

All the recorded data based on various variables underwent analysis using two-way analysis of variance to determine the effect of cultivars (Factor A), growing conditions (Factor B), and cultivars by agrophone interaction (A × B). Calculating the contribution of each factor to the total variance was in a percentage. Pearson correlation coefficients (*r*), upon usage, established the relationship between the soil moisture, humus content, and sugar dynamics (Rayimova *et al.*, 2024; Ergasheva *et al.*, 2024).

Table 1. Particle size distribution of soils in the study area.

Soil depth (cm)	Particle size distribution (mm), %	Physical clay (< 0.01 mm), %	Soil texture (USDA)
	Sand (> 0.25)	Silt (0.25–0.1)	Clay (0.1–0.05)
Irrigated (Control)			
0–30	0.8	0.2	17.3
30–50	1.2	0.3	3.7
Dry farming (Rainfed)			
0–30	0.6	0.3	15.8
30–50	1.0	0.4	4.5

Table 2. Humus and nutrient contents of soils in the study area.

Soil depth (cm)	Humus (%)	Total content (%)	C:N Ratio	Available nutrients (mg/kg)	Carbonates (CO ₂ , %)
		N	P		
Irrigated (Control)					
0–30	0.539	0.038	0.187	1.48	8.2
30–50	0.385	0.031	0.162	1.83	7.2
Dry farming (Rainfed)					
0–30	0.512	0.035	0.178	1.52	8.5
30–50	0.361	0.029	0.155	1.86	7.2

RESULTS

Pedological characteristics of the study area

The soil analysis conducted at the 'Ozodjon Obidjon Orif Farm' in the Nurobod District revealed a medium-loamy-textured soil under irrigated and rainfed conditions. According to the particle size distribution, the physical clay fraction (≤ 0.01 mm) in the 0–50 cm soil layer was slightly higher under dry farming conditions (34.1%–35.4%) than in the irrigated control (31.7%–33.9%) (Table 1). However, this minor increase in fine-dispersed particles in rainfed soils was ascribable to natural moistening and pedogenic processes under rainfed conditions.

Agrochemical analysis revealed the total humus content was generally low, ranging from 0.539% in the topsoil (0–30 cm) of irrigated fields to 0.361% in the subsoil (30–50 cm) of rainfed areas (Table 2). The availability of essential nutrients (nitrogen—N, phosphorus—P, and potassium—K) followed the same trend, being slightly higher in irrigated plots, which serves as a baseline for comparing the physiological responses of

wheat (*T. aestivum* L.) cultivars under diverse levels of environmental stress conditions.

Accumulation of soluble carbohydrates

In the tillering nodes of winter wheat cultivars (Antonina, Yaksart, Moskvich, and Ilgor), the monosaccharide and disaccharide concentrations entailed monitoring over three critical winter months (December, January, and March) (Figure 1).

Monosaccharide dynamics:

In the early wintering stage (December 20), monosaccharide levels revealed moderate effects from the agroecological conditions (Agrophone, Factor B), accounting for 7.0% of the total variance. However, as the cold hardening intensified by January 20, the genetic factor (cultivar, Factor A) became dominant, contributing 65.1% to the variance ($P \leq 0.044$). By the onset of spring (March 20), the genotype influence remained high at 69.4%, though it received a statistical category as nonsignificant ($P \leq 0.084$), suggesting a convergence in metabolic rates as vegetative growth resumed.

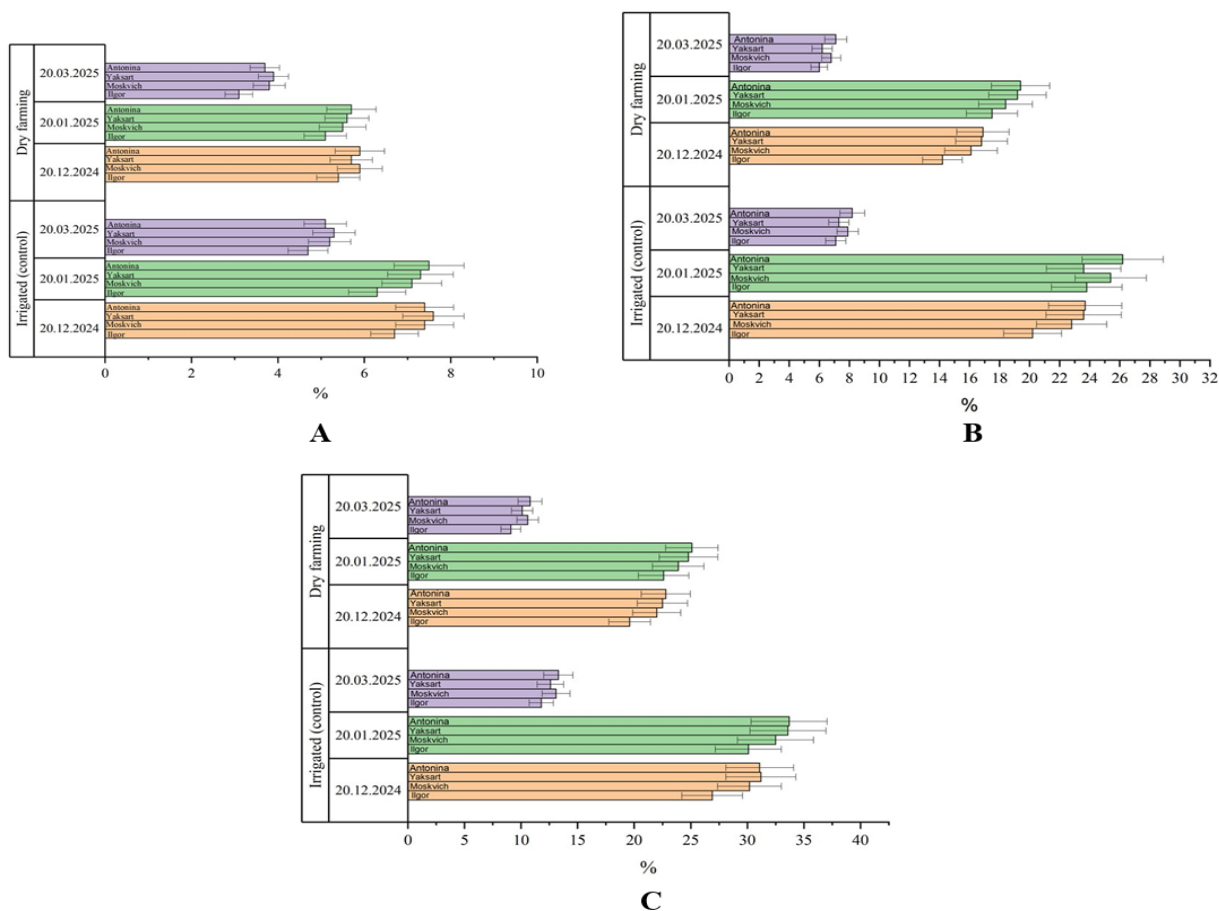


Figure 1. Effect of dryland (rainfed) cultivation on the monosaccharide (A), disaccharide (B), and total sugar (C) contents in the tillering nodes of winter wheat cultivars ($n = 6$, $P \leq 0.05$).

Disaccharide and total sugar accumulation (primarily sucrose) represented the largest fraction of soluble carbohydrates. In mid-winter (January), the cultivars (Factor A) accounted for 72.4% of disaccharide variation and 76.8% of total sugar variation ($P \leq 0.006$). Under rainfed conditions, the wheat cultivars exhibited a significantly higher sugar concentration than in the irrigated control, serving as a protective mechanism against dehydration and freezing conditions.

Analysis of variance and factors' contribution

The two-way analysis of variance provided a robust quantitative assessment of the drivers behind carbohydrate metabolism (Tables 3 to 5). For genetic potential (Factor A) across all

sampling dates and carbohydrate types, the wheat cultivars were the primary determinant of sugar levels, with their contribution ranging from 62.6% to 76.8%. The results confirmed that the ability to accumulate cryoprotective sugars was a robustly inherited trait.

In the environmental influence (Factor B), the growing conditions (irrigation vs. rainfed) had a highly significant ($P \leq 0.001$) effect under irrigated and water-stress conditions. Its contribution to total sugar variance was the highest in March (11.2%), reflecting the cumulative effect of water deficit conditions over the growing season. Interaction effects between the cultivars and growing conditions ($A \times B$) were consistently nonsignificant ($P \geq 0.05$), contributing only 1.2%–2.6% variance to the total variance.

Table 3. Two-way analysis of variance of the factors influencing carbohydrate content in winter wheat (sampled on December 20, $P \leq 0.05$).

Source of variation	d.f.	F-value	P-value	Significance	Factors contribution (%)
Monosaccharides					
Variety (A)	3	2.57	0.071	Ns	62.6
Agrophone (B)	1	68.64	<0.001	***	7.0
Interaction (A×B)	3	0.45	0.717	Ns	1.2
Residual (Error)	32	–	–	–	29.2
Disaccharides					
Variety (A)	3	3.14	0.039	*	71.8
Agrophone (B)	1	182.6	<0.001	***	8.4
Interaction (A×B)	3	0.88	0.460	Ns	2.1
Residual (Error)	32	–	–	–	17.7
Total sugars					
Variety (A)	3	4.26	0.012	*	74.5
Agrophone (B)	1	241.8	<0.001	***	9.8
Interaction (A×B)	3	1.02	0.390	Ns	2.6
Residual (Error)	32	–	–	–	13.1

Note: ns - nonsignificant; *** - significant ($P \leq 0.05$); **** - highly significant ($P \leq 0.001$); d.f. - degrees of freedom.

Table 4. Two-way analysis of variance of the factors influencing carbohydrate content in winter wheat (sampled on January 20, $P \leq 0.05$).

Source of variation	d.f.	F-value	P-value	Significance	Factor contribution (%)
Monosaccharides					
Variety (A)	3	3.02	0.044	***	65.1
Agrophone (B)	1	91.6	<0.001	****	7.4
Interaction (A×B)	3	0.74	0.53	Ns	1.9
Residual (Error)	32	–	–	–	25.6
Disaccharides					
Variety (A)	3	4.38	0.010	***	72.4
Agrophone (B)	1	214.3	<0.001	****	9.1
Interaction (A×B)	3	0.92	0.44	Ns	2.3
Residual (Error)	32	–	–	–	16.2
Total sugars					
Variety (A)	3	5.21	0.006	***	76.8
Agrophone (B)	1	268.9	<0.001	****	10.3
Interaction (A×B)	3	1.11	0.36	Ns	2.5
Residual (Error)	32	–	–	–	10.4

Note: ns - nonsignificant; *** - significant ($P \leq 0.05$); **** - highly significant ($P \leq 0.001$); d.f. - degrees of freedom.

Correlation and regression analysis

A significant ($P \leq 0.001$) negative correlation ($r = -0.84$) was evident between the soil moisture levels and total sugar content. Under rainfed conditions, the decrease in available soil water acts as a primary stressor, triggering the plant's adaptive response. Wheat plants actively synthesize and accumulate soluble sugars to maintain osmotic potential and

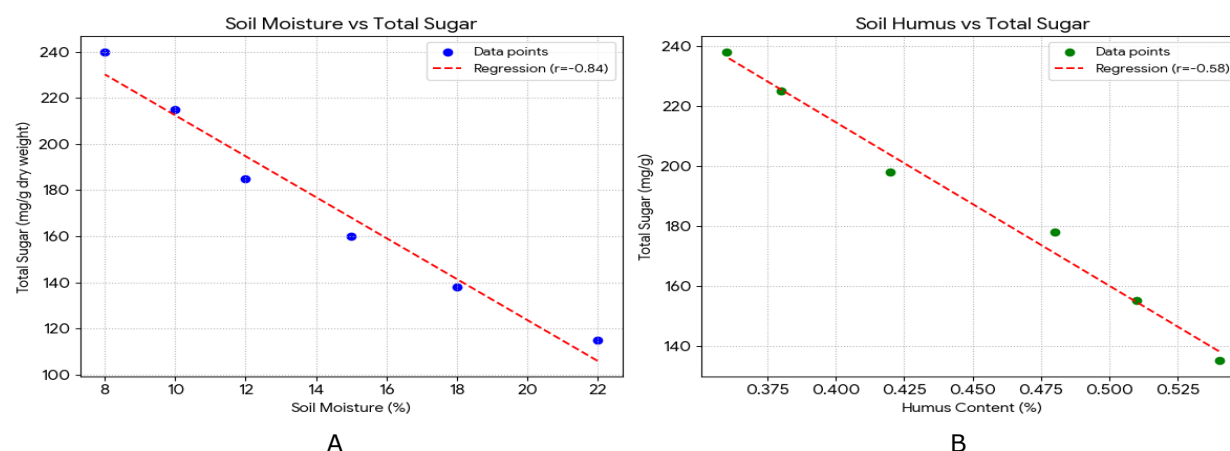
protect the cellular structures from dehydration and freezing. This mechanism proved crucial for enhancing the cryoprotective capacity of the tillering nodes during the wintering period (Figure 2A).

The correlation between soil humus content and sugar accumulation showed a moderate negative relationship ($r = -0.58$; $P \leq 0.001$). In soil layers with lower organic matter (0.36%–0.51% humus under dry farming), the

Table 5. Two-way analysis of variance of the factors affecting carbohydrate content in winter wheat (sampled on March 20, $P \leq 0.05$).

Source of variation	d.f.	F-value	P-value	Significance	Factor contribution (%)
Monosaccharides					
Variety (A)	3	2.41	0.084	***	69.4
Agrophone (B)	1	156.8	<0.001	****	6.1
Interaction (A×B)	3	0.68	0.57	Ns	1.5
Residual (Error)	32	–	–	–	23.0
Disaccharides					
Variety (A)	3	3.76	0.021	***	63.2
Agrophone (B)	1	97.4	<0.001	****	9.6
Interaction (A×B)	3	0.83	0.49	Ns	2.0
Residual (Error)	32	–	–	–	25.2
Total sugars					
Variety (A)	3	4.58	0.009	***	68.7
Agrophone (B)	1	132.5	<0.001	****	11.2
Interaction (A×B)	3	0.94	0.43	Ns	2.4
Residual (Error)	32	–	–	–	17.7

Note: ns - nonsignificant; *** - significant ($P \leq 0.05$); **** - highly significant ($P \leq 0.001$); d.f. - degrees of freedom.

**Figure 2.** Correlation between soil properties (moisture and humus content) and total sugar accumulation in winter wheat cultivars (A—Correlation between soil moisture [%] and total sugar accumulation in the tillering nodes of winter wheat under rainfed and irrigated conditions; and B—Impact of soil organic matter [humus, %] on the carbohydrate metabolism and sugar concentration of wheat cultivars).

wheat plants exhibited higher sugar concentrations than in the irrigated control. The results suggested that nutrient-limited environments further stimulate the metabolic shift toward carbohydrate storage as a survival strategy against environmental instability (Figure 2B).

According to the analysis of variance results, wheat cultivars (Factor A) were the dominant driver of sugar variation, accounting

for 74.5% to 76.8% of the total variance during the peak wintering stage (January). Meanwhile, growing conditions (Factor B) had the significant ($P \leq 0.001$) effect, and its contribution was relatively lower (10%). The results enunciated that while environmental stress (moisture and humus) triggers sugar synthesis, the magnitude of this accumulation had the primary dominance of genetic potential of the specific wheat cultivar.

DISCUSSION

The results revealed the carbohydrate metabolism in winter wheat (*T. aestivum* L.) was a highly dynamic process, significantly influenced by the interaction between genotypes' genetic potential, environmental management (Agrophone), and climatic variables. The peak accumulation of sugars in January was greatly analogous to the physiological mechanisms described in previous studies (Abdullaev, 1998; Blum, 2011). Furthermore, recent biotechnological strategies emphasized that sustainable cultivation under drought-stress conditions primarily depends on these physiological processes and adjustments (Slafer and Savin, 2005). The genotypic genetic capacity to regulate osmotic potential is a key factor in ensuring plant resilience under rainfed conditions (Zhuchenko, 2021).

As the temperature rises in March, stored sugars become mobile for plant growth and development. This transition from dormancy to active vegetation is a critical adaptive trait, similar to the physiological shifts observed in other arid-adapted species like *Artemisia absinthium* when established in water-limited environments (Ergashev *et al.*, 2025). The present results revealed a sharp decline in mono- and disaccharide levels during this period, serving as a marker for regrowth and development in spring.

The differential response to soil moisture under rainfed conditions highlighted the considerable role of environmental stressors. Studies on the ecological determinants of plant metabolites confirmed that local geobotanical conditions significantly influenced the biochemical composition and survival strategies of flora in the Samarkand Region, Uzbekistan (Tumanov, 1979; Istamkulova *et al.*, 2025). Moreover, improving soil fertility through organic amendments, such as vermicompost, can potentially mitigate some of these environmental stresses by enhancing the soil's water-holding capacity (Ergasheva *et al.*, 2024).

The dominance of the cultivar factor (76.8%) in the analysis of variance confirmed that climate resilience was primarily the genotypic genetic trait. Modern breeding and propagation techniques, including microclonal optimization, also aimed to preserve these high-value genetic traits for sustainable crop production (Sultonova *et al.*, 2025). Additionally, the use of endophytic bacteria has been evident to support wheat cultivation under salt and drought stress conditions, suggesting that future research could combine genetic selection with microbial applications (Akramov *et al.*, 2025).

CONCLUSIONS

The results expressed that carbohydrate accumulation in the tillering nodes of winter wheat (*T. aestivum* L.) was a highly dynamic process, primarily driven by genotypic genetic potential. The environmental factors, such as soil moisture and humus content, also significantly influenced sugar levels, and the magnitude of cryoprotective response was variety-specific. Under dry farming conditions, the increased concentrations of monosaccharides and disaccharides act as a vital osmotic adjustment mechanism against water stress and freezing conditions. Cultivars Yaksart and Ilgor exhibited superior sugar retention and stability compared with genotypes Antonina and Moskvich, proving them as more climate-resilient to the semi-arid conditions of Nurobod District. The results suggested that selecting cultivars with high genetic sugar-storage capacity was crucial for sustainable wheat production under water-limited environments.

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