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Root yield and technological quality of sugar beet as affected by harvest time under the conditions of the Western Forest-Steppe of Ukraine

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Abstract: This study evaluated the effects of hybrid, vegetation period duration, weather conditions, and harvest timing on sugar beet (*Beta vulgaris* L.) yield and technological quality under short-rotation cropping systems in the Western Forest-Steppe of Ukraine. Field experiments were conducted in 2022–2024 on commercial fields using six industrial hybrids and five harvest intervals from late September to mid-November. Root yield, sugar content, sugar yield, α-amino nitrogen, K^+ and Na^+, invert sugars, and the technological quality index (Iq) were assessed using ANOVA, correlation analysis, and principal component analysis (PCA). Extending vegetation from 185 to 200 days increased root yield by 11–12% and sugar yield by 0.8–1.2 t/ha. The optimal harvest window (10–25 October) provided the highest performance, with root yields of 68–73 t/ha, sugar content of 16.2–16.6%, and sugar yields of 14.6–16.3 t/ha. Early harvest resulted in reduced sugar content and Iq, whereas harvesting after 10 November did not increase yield and caused deterioration of technological quality due to elevated α-amino nitrogen and molasses-forming ions. PCA showed that over 85% of the total variation was explained by technological quality and moisture-related factors. Strube hybrids demonstrated greater stability under extended vegetation compared with KWS hybrids. These results define an optimal harvest window for maximising sugar beet productivity and quality under temperate meteorological conditions.

Keywords: sugar industry; storage; biomass accumulation; growing season

Optimising the timing of sugar beet (*Beta vulgaris* L.) harvesting is a critical component of contemporary production technologies aimed at obtaining high-quality raw material for the sugar industry. Under current conditions of climate change, shortened crop rotations, and increased phytosanitary pressure, aligning the length of the growing season with technological quality parameters has become particularly important (Curcic et al. 2018, Bastaubayeva et al. 2022, Makukh et al. 2025). In the Western Forest-Steppe zone of Ukraine, where the period of active plant growth ranges from 160 to 210 days, the selection of the harvest date directly affects the balance between yield accumulation, sugar content, and the stability of technological quality traits during storage (Hanhur and Filonenko 2024, Nowicki et al. 2025).

A key challenge is that traditional calendar-based approaches to determining harvest timing fail to consider differences in hybrid physiological maturity, prevailing weather conditions, and the accumulation

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of effective temperatures. As reported by Schnepel and Hoffmann (2016), even a modest delay in harvest by 10–15 days can shift the balance between biomass accumulation and sugar concentration, thereby reducing the technological value of the harvested crop.

In short-rotation cropping systems typical of Western Ukraine, a high proportion of sugar beet combined with repeated cultivation increases the risks of soil fatigue, phytopathological pressure, and disturbances in soil water balance (Li et al. 2024). Consequently, identifying the optimal harvest "window" should rely not only on calendar-based criteria but also on physiological and biochemical indicators of plant development as well as environmental conditions.

Photosynthesis, sucrose transport, and sucrose storage in sugar beet result from complex interactions among the leaf canopy, phloem transport pathways, and parenchyma cells of the storage root. According to Braun et al. (2014) and Braun (2022), carbohydrate partitioning is primarily governed by active phloem-loading mechanisms regulated by sucrose-sensing signalling pathways. Disruption of these processes due to temperature or water stress promotes the accumulation of reducing sugars, leading to a decline in recoverable sugar content.

Studies by Getz (2000) and Jammer et al. (2020) indicate that the development of sugar accumulation capacity in sugar beet roots proceeds through three distinct phases: initial biomass accumulation, transition to active carbohydrate storage, and stabilisation of sugar reserves. The duration of these phases largely determines the crop's productive potential. When the growing season is excessively prolonged beyond physiological maturity, the invertase enzyme complex is activated, leading to partial sucrose hydrolysis (Milford 2006).

Numerous studies have demonstrated that both yield and technological quality of sugar beet are closely linked to the length of the growing season. Hoffmann and Kenter (2018) reported that extending the growing period by 5–7 days within the temperature optimum of +8 to +12 °C results in an average yield increase of 1 t/ha. Field experiments conducted by Butt et al. (2016) showed that a 10-day delay in harvest increases sugar yield by approximately 0.7 t/ha. However, Wang et al. (2025) found that when temperatures fall below 0 °C, assimilate transport is markedly reduced, leading to a sharp decline in sugar content.

According to Bosemark (2006) and Hassani et al. (2018), differences among sugar beet hybrids are governed by the balance between biomass accumulation rates and the genetically determined potential for sucrose storage. Hybrids characterised by slower early growth but a prolonged period of active assimilation generally exhibit greater stability of technological quality traits at later harvest dates. Esmaeili et al. (2022) showed that adjustments in agronomic management, including delayed sowing, optimisation of plant density, and moisture regulation, can compensate for a shortened growing season without compromising yield.

In short crop rotations, as reported by Götze et al. (2017) and Hanhur and Filonenko (2024), sugar beet responds with reductions in both yield and the stability of technological quality. Li et al. (2024) demonstrated that extending rotation length improves soil microbial community structure and increases recoverable sugar yield by 15–20%.

According to Bastaubayeva et al. (2022) and Makukh et al. (2025), increasing temperatures and unstable water availability represent the primary constraints on autumn sugar beet harvesting in Central and Eastern Europe. FAO (2023) projects that the growing season of late crops in this region will shorten by 7–10 days by 2050. Agronomic modelling studies (Nowicki et al. 2025) further indicate that reducing the photoperiod below 11 h decreases dry matter accumulation by 15–18%, even under adequate thermal conditions.

An additional emerging challenge concerns the environmental quality of sugar products. Lima et al. (2025) were the first to report the presence of microplastics in commercial sugar samples, underscoring the need to improve post-harvest handling and processing standards.

Contemporary productivity forecasting systems, such as APSIM-Beet and DSSAT-Bv, enable simulation of the effects of temperature and photoperiod on sucrose accumulation in sugar beet (Gazdík et al. 2025). Hemayati et al. (2024) highlighted the importance of genotype × environment (G × E) analysis for optimising hybrid adaptation to specific agroecological regions. Wang et al. (2025) further confirmed that mean daily temperatures of 9–11 °C are optimal for maintaining the balance between root yield and recoverable sugar content.

Within the framework of technological quality control, ICUMSA (2023) standards remain the primary reference for evaluating sugar content and molasses-forming components, thereby enabling meaningful comparison of experimental results across international studies.

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The aim of this study was to determine the effects of harvest timing and growing season duration on root yield, sugar content, and total sugar yield in sugar beet cultivated within short-rotation cropping systems of the Western Forest-Steppe of Ukraine, while accounting for prevailing weather conditions. In addition, the study sought to develop an adaptive model for identifying the optimal harvest date based on the integration of field observations, thermal indicators, and hybrid-specific characteristics.

MATERIAL AND METHODS

Site description and experimental conditions. Field experiments were conducted during 2022–2024 on commercial fields of the private agricultural enterprise "Zakhidnyi Buh" located in the Lviv region of the Western Forest-Steppe of Ukraine (49°46'N, 24°08'E). The region is characterised by a temperate continental climate, with a mean annual air temperature of 8.4 °C, an average growing-season temperature of 15.2 °C, and an annual precipitation range of 650–720 mm.

Weather conditions varied markedly among the experimental years with respect to temperature and precipitation, enabling assessment of sugar beet responses to contrasting growth, development, maturation, and harvesting scenarios. The soil at the experimental site was classified as Haplic Chernozem according to the WRB (FAO) classification and had a silt loam texture, consisting of 35% sand, 12% clay, and 53% silt. The soil reaction was slightly acidic to neutral, with pH_{H_2O} of 6.6 and Sikora buffer pH of 6.86. The organic carbon content was 2.0%. The soil was characterised by a cation exchange capacity (CEC) of 24.1 $mmol_+$/100 g and the following available nutrient contents: P (Mehlich III) – 15.4 ppm, K (NH_4OAc, pH 7.0) – 175 ppm, Ca (NH_4OAc, pH 7.0) – 3 468 ppm, Mg (NH_4OAc, pH 7.0) – 260 ppm, and Na (NH_4OAc, pH 7.0) – 24 ppm. Base saturation was dominated by Ca (71.9%), followed by Mg (9.0%), K (1.9%), and Na (0.4%), while exchangeable acidity (H) accounted for 16% of the adsorption complex.

Plant material and experimental design. To meet the objectives of the study, a multifactorial field experiment was established within a long-term stationary trial (Table 1). Six commercially grown triploid sugar beet hybrids from different breeding companies were included, differing in biomass accumulation rate and sugar accumulation dynamics: KWS Koncertyna and KWS Lyudmyla; Strube Kerrol and Strube Bualo; and BTS 950 and BTS 705.

To simulate practical production conditions, five harvest-time intervals were defined (≤ 25 September; 25 September–10 October; 10–25 October; 25 October–10 November; > 10 November). This design allowed sensitive detection of shifts in technological parameters within a narrow temporal window of quantitative and qualitative yield formation. Treatments were arranged in a randomised complete block design with four replications. The net plot area was 50 m^2, while the gross plot area was 100 m^2.

All agronomic operations were conducted following precision crop production principles using appropriate equipment (Trimble GFX-750, DJI Mavic 3 Pro, Precision Planting), ensuring continuous monitoring of soil moisture and soil temperature throughout the growing season. Meteorological data were recorded using Davis Vantage Pro2 automatic weather stations at 10-min intervals.

Prior to sowing, the field was uniformly levelled, deep tillage was performed to a depth of 28–32 cm, and mineral fertilisers were applied at rates of N_{100}, P_{80}, and K_{120} (expressed as active substances). During the growing season, an integrated pest and disease management system was implemented in accordance with FRAC codes (2022–2024).

Sowing was conducted on 1 April 2022, 3 April 2023, and 5 April 2024. Full crop emergence occurred on 18 April 2022, 27 April 2023, and 25 April 2024. The length of the growing season, defined as the period from full emergence to harvest, ranged from 150 to 210 days.

Table 1. Experimental layout: yield and quality of sugar beet hybrids as affected by harvest timing

Hybrid (Factor A)	Harvest timing (Factor B)	Calendar period
KWS Koncertyna	early harvest (E)	≤ 25 September
KWS Lyudmyla	medium-early harvest (ME)	25 September–10 October
Strube Kerrol	medium harvest (M)	10–25 October
Strube Bualo	medium-late harvest (ML)	25 October–10 November
BTS 950	late harvest (L)	> 10 November
BTS 705		

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Weather conditions were assessed using several analytical approaches. For comparative analysis of mean daily air temperature and total precipitation, deviation significance coefficients (*DSC*) were calculated to quantify differences between the conditions of individual years and long-term climatic averages using the following Eq.:

$$DSC = \frac{(X_i - \overline{X})}{\sigma} \quad (1)$$

where: *DSC* – deviation significance coefficient; Xi – observed weather variables for a given period; $\overline{X}$ – corresponds to the long-term mean value; σ – standard deviation. The magnitude of *DSC* was interpreted according to the following classification: *DSC* < 1 indicates conditions close to the long-term norm; *DSC* values between 1 and 2 indicate conditions that significantly deviate from long-term averages; and *DSC* > 2 denotes conditions approaching rare or extreme events (Rozhkov et al. 2016).

Determination of biometric and technological parameters. Root yield (t/ha), sugar content (%), sugar yield (t/ha), and invert sugars (%) were determined. Root yield was calculated from the mass of harvested sugar beet roots collected from the experimental plots and recalculated to the hectare.

Sugar content was determined polarimetrically using a saccharimeter in accordance with ICUMSA methods (ICUMSA 2023).

Molasses-forming elements, potassium (K) and sodium (Na), were determined by flame photometry at wavelengths of 766.5 and 589.6 nm, respectively, using a Sherwood 410 flame photometer.

α-amino nitrogen (mg/100 g) was determined colourimetrically by reaction with ninhydrin at 570 nm, following ICUMSA procedures (ICUMSA 2023).

Invert sugars were determined using the Lane-Eynon method, particularly for late harvest dates.

Sample preparation involved cleaning the sugar beet roots, chopping, and homogenising a subsample corresponding to 10% of the total mass. The homogenate was clarified using lead acetate, diluted to a final volume of 200 mL, and filtered prior to analysis, following the procedure described by Lima et al. (2025).

The technological quality index (Iq) was calculated according to Alami et al. (2021) using the following Eq.:

$$I_q = Sucrose + 0.5\,(K + Na) - 0.25(\alpha N) \quad (2)$$

Statistical analysis. To evaluate the effects of vegetation period duration and harvest time on yield and quality parameters, one-way analysis of variance (ANOVA) was applied using $LSD_{00.5}$ and $LSD_{0.01}$ as post-hoc significance criteria. Only sugar processing parameters were compared using Tukey's *HSD* (honestly significant difference) test. Data normality was assessed using the Shapiro-Wilk test.

Pearson's correlation analysis was performed to assess relationships among sugar content, technological quality index, root yield, and invert sugars.

Multivariate relationships were explored using principal component analysis (PCA), following the approaches described by Alami et al. (2021) and Nowicki et al. (2025).

All statistical analyses were conducted using R software (version 4.3.1, Boston, USA) and Statistica (version 13.5, Tulsa, USA).

Experimental reproducibility was confirmed by coefficients of variation below 10%, correlation coefficients between replicates ranging from r = 0.89 to 0.96, and reliability coefficients (K) greater than 0.95. The analytical error of chemical determinations did not exceed ± 2%.

RESULTS

Weather conditions. Weather conditions were analysed for the years of the experiment and compared with long-term average data for the period 2002–2021. Meteorological conditions during the vegetation period varied considerably from year to year. Mean daily air temperatures substantially exceeded the long-term averages recorded for 2002–2021 (Table 2).

Spring 2022 was characterised by early warming (mean April temperature of +10.1 °C), which resulted in full crop emergence 18 days after sowing. In contrast, cooler conditions were observed in 2023 (mean April temperature of +7.6 °C), delaying emergence to 24–25 days after sowing. In 2024, the thermal regime was close to the long-term average, and the active growth period was the longest, lasting up to 210 days.

The sum of active temperatures (> 5 °C) ranged from 2 730 to 3 060 °C, providing sufficient thermal energy for completion of the growth cycle and sucrose accumulation. Mean relative air humidity during September–November ranged from 73% to 82%.

The study years differed substantially in terms of precipitation amounts, both among years and relative to long-term averages (Table 3). Precipitation during the active vegetation period was highest in

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Table 2. Mean daily air temperature and coefficients of significance of deviation from long-term averages

Month	T_{ma} (°C) 2002–2021	Mean daily air temperatures (°C)				*DSC*		
		2022	2023	2024	2022–2024	2022	2023	2024
January	–4.8	–0.78	2.0	–1.3	0.03	2.2	3.7	1.9
February	–3.2	2.20	0.20	5.60	2.67	1.6	1.0	2.7
March	1.9	2.01	5.00	5.80	4.27	0.1	1.5	1.9
April	8.4	6.90	8.1	12.0	9.00	–0.7	–0.1	1.6
May	14.2	14.8	14.3	16.4	15.2	0.3	0.0	1.0
June	18	20.1	17.7	19.9	19.2	1.9	–0.3	1.7
July	20	19.6	20.5	21.9	20.7	–0.4	0.5	1.9
August	19.5	20.1	21.8	21.5	21.0	0.4	1.6	1.4
September	14.4	12.3	18.3	18.2	21.1	–0.7	1.4	1.4
October	8.1	11.0	12.2	9.8	11.1	1.6	2.2	0.9
November	3.1	4.19	4.3	2.8	3.76	0.9	1.0	–0.3
December	–2.2	0.74	1.2	0.9	2.84	5.2	6.1	5.5
Annual average	8.1	9.44	10.5	11.1	10.4	1.8	3.3	4.1

T_{ma} – multi annual air temperatures; *DSC* – deviation significance coefficient. The calculation and analysis of the coefficients of significance for deviations of mean daily air temperatures from long-term averages showed that, over the three-year study period (36 months), 15 months (41.7%) were classified as typical conditions, 15 months (41.7%) exhibited significant deviations from long-term mean temperatures, and 6 months were classified as rare conditions

2024, which substantially contributed to the formation of the highest yield level.

Root yield. The mean sugar beet root yield across the experiment over three years was 65.8 t/ha, ranging from 59.4 t/ha in 2022 to 71.5 t/ha in 2024. Extension of the vegetation period by 10 days increased root yield by an average of 2.7 t/ha (r = 0.82; P < 0.05).

Among the tested hybrids, Bualo (Strube) and BTS 950 exhibited the highest yield performance, which was associated with prolonged maintenance of leaf area during the autumn period (LAI > 3.2). KWS Koncertyna showed rapid early growth and early yield formation; however, under late-harvest conditions, it lost up to 5% of root mass due to tissue reduction (Figure 1).

Table 3. Sum of precipitation and deviation significance coefficients

Month	Sum of precipitations (mm)					*DSC*		
	2002–2021	2022	2023	2024	2022–2024	2022	2023	2024
January	32.2	29.0	28.8	45.8	34.5	–1.25	–1.74	5.89
February	31.6	16.8	24.8	35.6	30.2	–5.80	–3.60	1.41
March	37.2	9.4	34.4	72.6	53.5	–10.91	–1.12	8.46
April	38.5	52.2	73.6	49.8	61.7	5.53	7.43	3.80
May	80.2	32	15.6	16	15.8	–19.7	–57.6	–35.1
June	81.0	55	85.8	115.8	100.8	–11.1	0.89	4.42
July	80.5	87.6	110.8	113.6	112.2	3.13	3.47	6.34
August	62.1	60.6	51.4	19.2	35.3	–0.65	–2.95	–21.74
September	51.2	149.4	15.4	36.6	26.0	43.3	–26.3	–5.81
October	42.7	34.6	49.6	19.4	34.5	–3.59	1.98	–10.59
November	33.5	33.8	41.2	20.2	30.7	0.11	3.35	–9.00
December	39.2	56.4	21.4	27.2	24.3	7.53	–13.4	–6.39
Average per month	50.8	51.4	46.1	47.7	46.9			
Σ per year	609.9	616.8	552.8	571.8	559.5			

DSC – deviation significance coefficient

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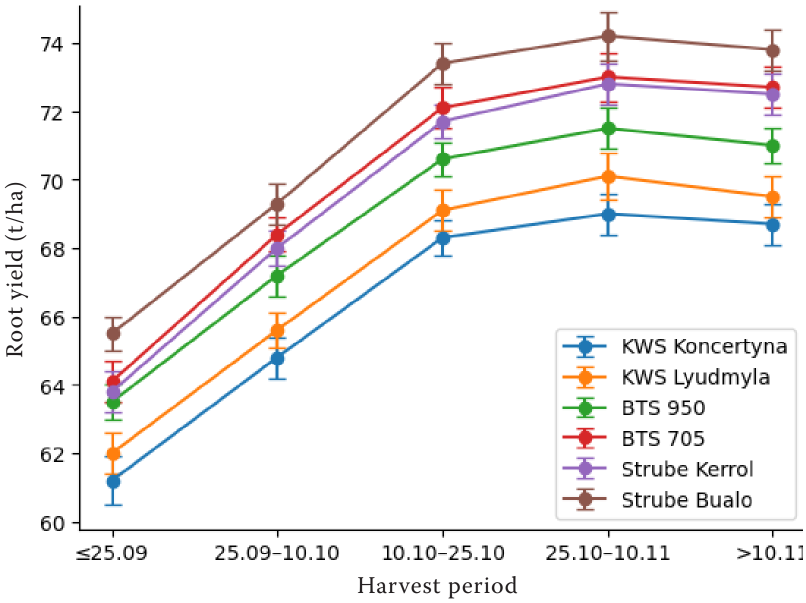

Figure 1. Dynamics of sugar beet yield as affected by harvest date (2022–2024)

The range of root yield variation across all studied factors extended from 60.5 t/ha (hybrid BTS 705, 2023, early harvest date) to 82.5 t/ha (hybrid Kerrol, 2024, medium–late harvesting time). The highest yields were recorded in 2024 for the third and fourth harvest dates (Table 4).

Sugar content. Sugar content varied significantly with harvest date (Tables 5 and 6) and the prevailing weather conditions during the study year.

The generalised analysis of variance indicated that harvest date was the dominant factor determining sugar content in sugar beet, accounting for the largest proportion of explained variance and exhibiting a high level of statistical significance ($P < 0.001$). The increase in sugar content from early harvest dates (15.1–15.3%) to optimal harvest dates (16.3–16.7%) was consistent with dry matter accumulation, a reduction in invert sugars, and improved technological juice parameters.

Table 4. Root yield of sugar beet hybrids as affected by harvest date and year conditions (t/ha)

Harvest timing (Factor B)		Hybrid (Factor A)					
		KWS Koncertyna	KWS Lyudmyla	Strube Kerrol	Strube Bualo	BTS 950	BTS 705
2022	E	63.5[a]	62.5[a]	64.5[ab]	62.0[a]	64.0[ab]	61.5[a]
	ME	68.5[b]	67.5[b]	69.5[b]	67.0[b]	69.0[b]	66.5[b]
	M	73.5[c]	72.5[c]	74.5[c]	72.0[c]	74.0[c]	71.5[bc]
	ML	74.5[c]	73.5[c]	75.5[d]	73.0[c]	75.0[d]	72.5[c]
	L	72.5[c]	71.5[bc]	73.5[c]	71.0[bc]	73.0[c]	70.5[bc]
2023	E*	62.5[a]	61.5[a]	63.5[a]	61.0[a]	63.0[a]	60.5[a]
	ME	67.5[b]	66.5[b]	68.5[b]	66.0[b]	68.0[b]	65.5[ab]
	M	72.5[c]	71.5[bc]	73.5[c]	71.0[bc]	73.0[c]	70.5[bc]
	ML	73.5[c]	72.5[c]	74.5[c]	72.0[c]	74.0[c]	71.5[bc]
	L	71.5[bc]	70.5[bc]	72.5	70.0[bc]	72.0[c]	69.5[bc]
2024	E*	70.5[bc]	69.5[bc]	71.5[bc]	69.0[bc]	71.0[bc]	68.5[b]
	ME	75.5[d]	74.5[cd]	76.5[d]	74.0[d]	76.0[d]	73.5[c]
	M	80.5[e]	79.5[e]	81.5[e]	79.0[e]	81.0[e]	78.5[e]
	ML	81.5[e]	80.5[e]	82.5[e]	80.0[e]	82.0[e]	79.5[e]
	L	79.5[e]	78.5[e]	80.5[e]	78.0[e]	80.0[e]	77.5[e]

Harvest dates: E – early; ME – medium-early; M – medium; ML – medium-late; L – late; Superscripts denote groups of means that are not significantly different at $LSD_{0.05}$

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Table 5. ANOVA results for sugar content

Effect	*df*	MS	*F*	*P*-value
Hybrid (A)	5	0.42	3.58	**0.006***
Harvesting time (B)	4	4.85	41.3	**< 0.001****
Year (C)	2	0.31	2.66	0.074
A × B	20	0.12	1.03	0.42
A × C	10	0.07	0.60	0.80
B × C	8	0.15	1.28	0.26
Error	96	0.117		

The hybrid genotype also had a significant effect on sugar content ($P = 0.006$), confirming genetic differences among cultivar types in sucrose accumulation capacity. In contrast, the effect of year showed only a marginal trend ($P \approx 0.074$), indicating a relatively stable hybrid response over the three years. The absence of significant interactions among hybrids, harvest dates, and years suggests that the observed patterns were consistent across genotypes, with all hybrids responding similarly to shifts in harvest timing.

In 2022, the mean sugar content at harvest before 25 September was 15.1%, increased to 16.0% during the first 10-day period of October, and reached 16.6% at late-harvest dates (> 10 November) (Table 7). However, late harvest was accompanied by increased α-amino N and molasses-forming ions, which reduced the technological sugar recovery coefficient.

The longest vegetation period (210 days in 2024) coincided with the highest cumulative photothermal index (FTI = ΣT/days = 14.6 °C/day), resulting in the maximum sugar yield (16.4 t/ha). Shorter vegetation periods (< 180 days) were associated with a 10–14% reduction in biomass and a 0.9–1.3% decrease in sugar content.

During crop development, a consistent pattern was observed: increases in sugar content beyond 190 days of vegetation were accompanied by a deterioration of the technological quality index by 7–8%. This trend is consistent with the findings of Wang et al. (2025) and Hoffmann and Kenter (2018), who reported that prolonged vegetation periods at temperatures below +4 °C increase invertase activity and reduce net sugar recovery.

Based on the mean sugar yield, two hybrid groups were identified. The high-performing group (Strube Bualo, BTS 705) achieved sugar yields of 15.8–16.4 t/ha, whereas the moderate-performing group (KWS Koncertyna, Lyudmyla, BTS 950) produced 13.9–14.6 t/ha. Strube hybrids exhibited the highest inter-annual stability ($CV = 6.2\%$), while KWS Lyudmyla showed a stronger dependence on thermal conditions ($r = 0.77$ with ΣT).

Table 6. Sugar content of sugar beet roots as affected by harvest date and year, weather conditions (%)

Harvesting time (Factor B)		Hybrid (Factor A)					
		KWS Koncertyna	KWS Lyudmyla	Strube Kerrol	Strube Bualo	BTS 950	BTS 705
2022	E*	15.0^{d}	15.1^{d}	15.2^{c}	14.9^{d}	15.2^{d}	14.9^{d}
	ME	15.6^{c}	15.5^{c}	16.1^{b}	15.7^{c}	16.1^{c}	15.4^{c}
	M	16.2^{b}	16.3^{b}	16.3^{b}	16.3^{b}	16.2^{b}	16.1^{b}
	ML	16.5^{a}	16.5^{a}	16.4^{ab}	16.5^{a}	16.8^{a}	16.4^{a}
	L	16.6^{a}	16.6^{a}	16.6^{a}	16.6^{a}	16.8^{a}	16.6^{a}
2023	E*	14.9^{d}	14.8^{d}	15.0^{c}	14.8^{d}	15.0^{c}	15.0^{c}
	ME	15.3^{c}	15.3^{c}	15.6^{b}	15.5^{c}	16.0^{b}	15.2^{c}
	M	15.9^{b}	16.1^{b}	16.1^{a}	16.0^{b}	16.1^{b}	16.0^{b}
	ML	16.3^{a}	16.2^{a}	16.2^{a}	16.1^{ab}	16.3^{a}	16.2^{a}
	L	16.4^{a}	16.4^{a}	16.3^{a}	16.3^{a}	16.4^{a}	16.3^{a}
2024	E*	15.3^{d}	15.3^{d}	15.7^{c}	15.4^{d}	15.3^{c}	15.2^{c}
	ME	16.1^{c}	16.2^{c}	16.3^{b}	16.2^{c}	16.1^{b}	16.0^{b}
	M	16.6^{b}	16.7^{b}	16.5^{b}	16.7^{b}	16.3^{b}	16.6^{b}
	ML	17.1^{a}	16.9^{a}	16.7^{a}	16.9^{a}	16.9^{a}	16.9^{a}
	L	17.3^{a}	17.2^{a}	17.0^{a}	17.2^{a}	17.1^{a}	17.2^{a}

Harvest dates: E – early; ME – medium-early; M – medium; ML – medium-late; L – late; Superscripts denote groups of means that are not significantly different at $LSD_{0.05}$

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Table 7. Root quality parameters as affected by harvest date (mean for 2022–2024)

Harvesting time	Sugar content (%)	α-amino N (mg ×100/g)	K + Na (mmol × 100/g)	Quality index	Invert sugar (%)
E*	15.1 ± 0.4[c]	13.5 ± 0.6[ab]	5.8 ± 0.3[ab]	12.0[c]	0.18[b]
ME	15.8 ± 0.3[b]	12.2 ± 0.4[c]	5.2 ± 0.2[c]	12.9[ab]	0.14[c]
M	16.3 ± 0.5[ab]	11.8 ± 0.5[c]	5.0 ± 0.3[c]	13.4[a]	0.12[c]
ML	16.5 ± 0.4[a]	12.6 ± 0.5[bc]	5.3 ± 0.2[c]	13.0[ab]	0.16[bc]
L	16.6 ± 0.6[a]	13.8 ± 0.7[a]	5.9 ± 0.4[a]	12.5[bc]	0.21[a]

Harvest dates: E – early; ME – medium-early; M – medium; ML – medium-late; L – late; Superscripts denote groups of means that are not significantly different according to Tukey's *HSD* (honestly significant difference) test at $P \leq 0.05$

Correlation and regression analyses revealed strong relationships between:
- vegetation duration (D) and root yield (r = 0.82; P < 0.01);
- sugar content and ΣT (r = 0.79; P < 0.05);
- Iq and the K/Na ratio (negative correlation, r = –0.73).

A second-order regression model describing sugar yield was defined as:

$$Y = -28.64 + 0.41D - 0.001D2 + 0.32T - 0.008T^2 \quad (R^2 = 0.86);$$

where: Y – sugar yield (t/ha); D – vegetation duration (days); T – mean air temperature during the autumn period (°C). The model optimum was identified at D = 197 days and T = 10.2 °C, which closely corresponds to the average field observations.

PCA. The principal component analysis indicated that most of the variation in root quality parameters

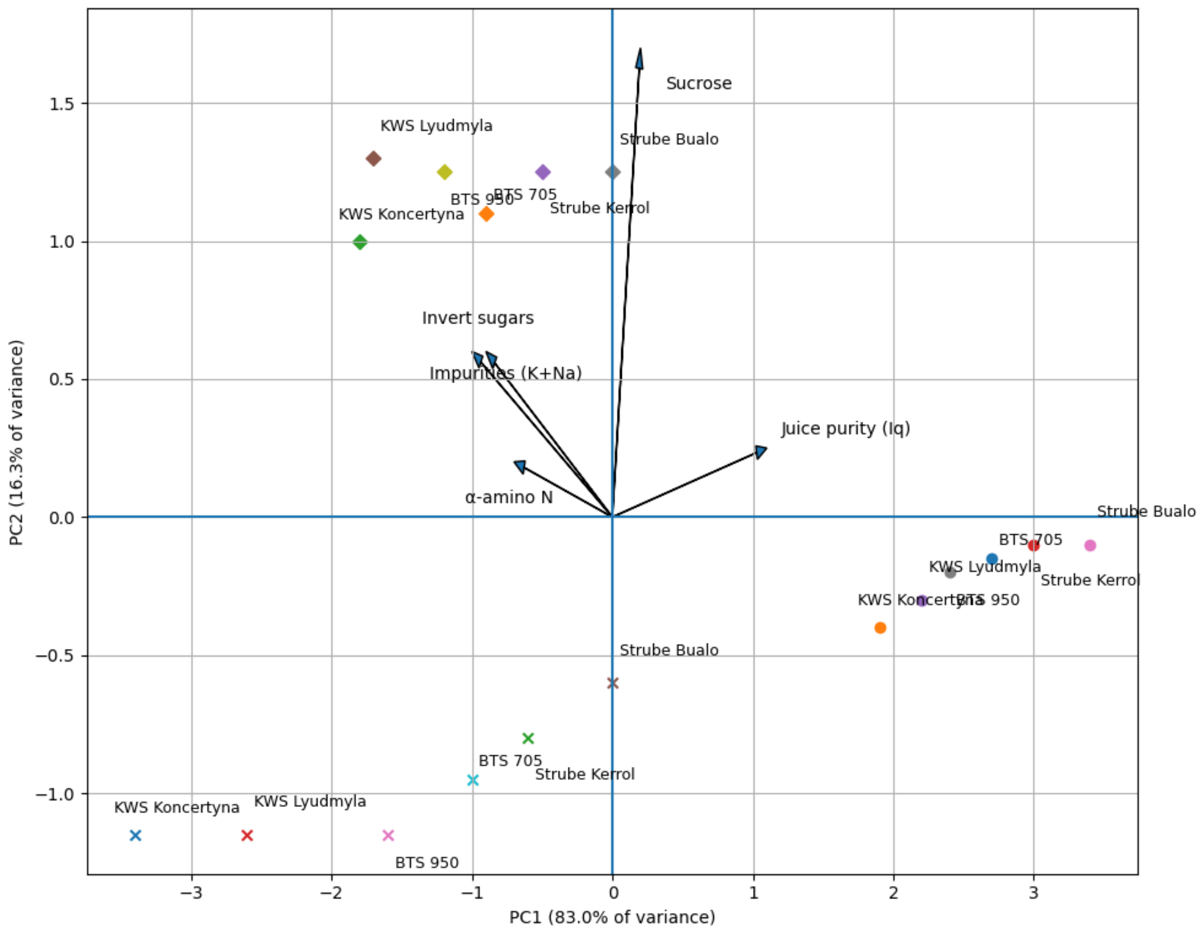

Figure 2. Principal component analysis (PCA) biplot of sugar beet root quality parameters as affected by hybrid and harvest date

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was explained by the first two principal components. PC1 (≈ 65%) and PC2 (≈ 22%) together accounted for more than 87% of the total variability (Figure 2).

PC1 represents a gradient of technological value and is primarily associated with high sucrose content and a high technological quality index, whereas elevated concentrations of $K^+ + Na^+$ ions and α-amino nitrogen negatively affect juice purity. PC2 reflected the influence of invert sugars and, to a lesser extent, α-amino nitrogen, contributing to the vertical dispersion of samples in the biplot.

The PCA biplot clearly shows sample grouping by harvest date. Early harvest dates (≤ 25 September; red points) are located in the region characterised by lower sucrose content and lower technological quality index, indicating incomplete physiological maturity of the roots. Optimal harvest dates (10 October–10 November; green points) are clustered in the right-hand sector of the biplot, corresponding to the highest values of technological parameters, including maximum sucrose content, high juice purity, and minimal concentrations of molasses-forming compounds. Late-harvest dates (> 10 November; blue points) are shifted toward higher $K^+ + Na^+$ and α-amino nitrogen contents, indicating a decline in technological quality associated with overmaturity and the accumulation of secondary metabolic products.

In addition, the PCA biplot highlights genetic differences among hybrids. Strube hybrids (Bualo, Kerrol) are positioned in the region of high sucrose content and high Iq values, indicating greater stability of technological properties under prolonged vegetation. In contrast, KWS hybrids (Koncertyna, Lyudmyla) tend toward regions with elevated α-amino nitrogen and $K^+ + Na^+$ contents, suggesting greater sensitivity to weather variability and an increased risk of quality deterioration under late-harvest conditions.

Principal component analysis confirmed that the optimal harvest window (10–25 October) provides the best balance between yield and technological quality. In contrast, excessively early or late harvest is associated with degradation of juice quality parameters. These results are consistent with previous long-term studies, which identified sugar beet quality variation as being driven by the combined effects of hybrid genetic characteristics and vegetation period duration.

Overall, the obtained data showed that the most favourable combination of root yield, sugar content, sugar yield, and technological quality was achieved when sugar beet was harvested between 10 and 25 October. Extending the vegetation period beyond this interval did not result in further improvement in the main productivity indicators and, in several cases, was associated with deterioration in juice quality due to increased α-amino nitrogen and combined potassium and sodium concentrations. The tested hybrids differed in their responses to harvest timing, with the Strube hybrids generally demonstrating greater stability in yield and quality traits across the studied harvest dates.

DISCUSSION

The results of the three-year study confirm that vegetation period duration and harvest timing are the key determinants of sugar beet root yield, sugar content, and sugar yield. In the Western Forest-Steppe of Ukraine, where the active vegetation period lasts 150–210 days, a clear relationship was identified between the duration of the photosynthetically active period, temperature dynamics during September–October, and the intensity of root dry matter accumulation.

Field observations demonstrated that the optimal harvest window (10–25 October) ensured the highest yield and quality parameters across all tested hybrids, with root yields of 68–73 t/ha, sugar content of 16.2–16.6%, and corresponding sugar yields of 14.6–16.3 t/h. These findings are consistent with the conclusions of Hoffmann and Kenter (2018), who reported that extending the vegetation period until mean daily temperatures decline below 10 °C enhances sugar yield by prolonging leaf assimilatory activity and continued sucrose accumulation in root parenchyma.

The present results also corroborate the findings of Alami et al. (2021), who showed that delaying harvest by 10–15 days increases sucrose concentration by 0.6–1.1%, whereas an excessively late harvest (> 10 November) leads to a higher proportion of invert sugars and losses in technological quality. In the current study, hybrids BTS 950 and Strube Bualo exhibited increased α-amino nitrogen (12.5–13.1 mg/100 g) and elevated K^+ and Na^+ concentrations (5.5–5.7 mmol/100 g) after 10 November, indicating intensified cell membrane degradation processes at temperatures below +3 °C.

A similar pattern was reported by Wang et al. (2025) in experiments conducted in Northern China, where minimum temperatures below 0 °C resulted

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in a sharp decline in sucrose accumulation due to reduced phloem activity and increased post-harvest losses (Zhang et al. 2017). Their findings indicated that optimal harvest conditions are associated with mean daily temperatures of approximately 10 °C and minimum temperatures not lower than 0 °C, which fully aligns with the results obtained under late-autumn conditions in the Western Forest-Steppe of Ukraine.

Root yield during the first two harvest periods (up to 25 September–10 October) was 10–15% lower than at the optimal harvest time. This reduction can be attributed to incomplete development of the assimilatory apparatus and insufficient formation of additional cambial rings, which play a key role in secondary thickening (Milford 2006). According to Jammer et al. (2020), the maximum enzymatic activity of sucrose-synthesising complexes occurs approximately 70–90 days after emergence, which determines the subsequent intensity of sugar accumulation. In the present study, the phase of active sugar accumulation occurred 130–170 days after sowing (i.e., 80–120 days after full emergence), after which the rate of yield increase gradually declined.

Among the tested hybrids, KWS Lyudmyla and Strube Kerrol showed a stable response to extended vegetation, with yield increases of 7–8% and sugar yields reaching 15.2–16.0 t/ha. In contrast, BTS 705 and Strube Bualo showed more rapid biomass accumulation but greater sensitivity to excess moisture and early November frosts. These results confirm that hybrids with a moderate biomass accumulation rate exhibit greater stability of technological quality during the late vegetation period, in agreement with the findings of Antošovský et al. (2021) and Webster et al. (2016).

Sugar content increased from 15.0–15.8% at early harvest dates to 16.6–16.8% at optimal harvest dates, after which it remained stable or slightly decreased under conditions of excess moisture in November. The increase in sugar content occurred in parallel with a reduction in α-amino nitrogen and the potassium-sodium complex, supporting the hypothesis of an inverse relationship between tissue nitrogen status and sucrose accumulation (Ramadan 2005, Milford 2006, Hoffmann and Kenter 2018).

Later harvest promoted partial remobilisation of nitrogen from leaves to roots, thereby increasing the risk of elevated concentrations of molasses-forming substances, particularly when daily air temperatures dropped below 5 °C (Tsialtas and Maslaris 2013). These observations are consistent with the conclusions of Koocheki et al. (2004) and Kiskini et al. (2016), who reported increased invert sugar content and reductions in white sugar yield of up to 8% under late harvest conditions (> November). Correlation analysis (r = 0.82 between root yield and sugar yield; r = –0.68 between sugar content and the sum of K + Na) indicates a high degree of integration among physiological processes during the late vegetation phase.

Extension of the growth period by 10–15 days resulted in a yield increase of 3.5–4.5 t/ha, corresponding to a 0.8–1.2 t/ha increase in sugar yield. However, further delay in harvest (> 10 November) did not provide a statistically significant advantage ($LSD_{0.05}$ = 1.2 t/ha) due to sugar losses associated with physiological ageing and an increased proportion of non-sugars.

Notably, Strube hybrids exhibited higher technological quality index values (Iq > = 15.9–16.3) within the optimal harvest window, indicating a more favourable balance between sugar content and molasses-forming elements. This observation is consistent with Bosemark's (2006) findings, which demonstrated that genetic characteristics influence the balance between root mass and sucrose concentration. In the present study, this balance was most optimal at intermediate harvest dates (10–25 October).

Pavlu et al. (2017) reported that early harvesting (before the end of September) results in a 10–15% yield loss due to incomplete root maturity. In contrast, late harvesting (after 10 November) increases the concentration of molasses-forming ions. Using principal component analysis, Alami et al. (2021) demonstrated that variations in sucrose content and the concentrations of K^+, Na^+, and α-amino nitrogen (αN) account for more than 80% of the variability in technological quality parameters associated with harvest timing.

During the late vegetative period, a decrease in temperature to 5–8 °C reduces respiratory activity, thereby slowing sucrose degradation, while photosynthesis continues to ensure a net gain of carbohydrates. However, prolonged exposure to temperatures below 0 °C induces the opposite effect, promoting the inversion of sucrose into glucose and fructose (Zhou et al. 2024). This physiological response explains why, in the present study, the optimum sugar yield was achieved at mean daily temperatures of 9–11 °C and a vegetation duration of 175–185 days. Comparison with the findings of Jammer et al. (2020) and Elliott and Weston (1993) confirms that this period corresponds to the formation of the maximum number of

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active cambial rings and parenchymatous cells with high vacuolar capacity in sugar beet roots, providing the morphological basis for sucrose accumulation.

Comparison of the present results with those obtained in Central European regions (Kenter and Hoffmann 2009, Webster et al. 2016, Antošovský et al. (2021)) and northern Chinese agroecological zones (Zhou et al. 2024) indicates that the temperature-moisture profile of the Western Forest-Steppe is most similar to the German or Polish agroclimatic type. Therefore, recommendations to complete harvest by 25 October can be considered broadly applicable under these conditions.

In regions characterised by a shorter autumn photoperiod and a higher risk of early frost events (e.g., Northern China and Northern Poland), the optimal harvest window shifts earlier, typically to 5–15 October. In contrast, under milder climatic conditions, harvest can be extended until early November without significant losses in sugar content. Overall, the synthesis of these results allows classification of optimal thermal and phenological conditions for defining a "harvest window", providing a promising basis for modelling sugar beet harvest timing.

From an agronomic and technological perspective, the results indicate that the harvest window for sugar beet in the Western Forest-Steppe of Ukraine should be optimised not only for maximum root biomass accumulation but also for maintenance of processing quality. Although prolonged field retention may support continued biomass formation under favourable conditions, delayed harvesting increases the risk of quality losses associated with the accumulation of molasses-forming compounds. It reduces the technological suitability of roots for sugar production. Therefore, harvesting during the second and third decades of October appears to be the most rational management strategy, as it provides the best compromise between productivity, sugar accumulation, and the industrial quality of the raw material under the studied environmental conditions.

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