

Mass loss, sucrose depletion and technological quality changes in sugar beet roots tubers during long-term field clamp storage under commercial conditions

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Abstract: The study assessed changes in root mass, sucrose content, technological impurities, and microbial polysaccharides in sugar beet tubers during long-term field clamp storage under commercial conditions in the Western Forest-Steppe of Ukraine in 2024–2025. Tubers of commercial hybrids were stored in outdoor clamps and sampled after 0, 30, 60, 90, 120, 150, and 180 days. Tuber mass loss, sucrose content, K, Na, α -amino nitrogen, and dextran/levan accumulation were determined using standard analytical methods. Tuber mass loss increased from 0.85 % after 30 days to 9.20 % after 180 days. Sucrose content declined from 18.30 % at harvest to 17.17 % after 180 days, corresponding to a relative sucrose loss of 6.17 %. Potassium increased from 3.85 to 5.31 mmol 100 g⁻¹, sodium from 0.48 to 1.03 mmol 100 g⁻¹, and α -amino nitrogen from 11.8 to 27.8 mg 100 g⁻¹. Dextran/levan accumulation remained low during the first 90 days but increased sharply after 120 days, reaching 3.31 % by day 180. The results indicate that outdoor clamp storage should not exceed 120 days under these conditions.

Key words: sugar beet, clamp, long-term storage, sucrose content, dextran, levan, technological quality, α -amino nitrogen

Izguba mase, upad saharoze in tehnološke spremembe koreninskih gomoljev sladkorne pese med dolgotrajnim skladiščenjem v komercialnih razmerah

Izvleček: Študija je ocenila spremembe v masi koreninskih gomoljev, vsebnosti saharoze, tehnoloških nečistoč in mikrobnih polisaharidov v gomoljih sladkorne pese med dolgotrajnim skladiščenjem v komercialnih razmerah v gozdni stepi zahodne Ukrajine v letih 2024–2025. Gomolje komercialnih hibridov so skladiščili v pokritih poljskih jamah in jih vzorčili po 0, 30, 60, 90, 120, 150 in 180 dneh. Izgubo mase gomoljev, vsebnosti saharoze, K, Na, α -amino dušikovih spojin in kopičenje dekstrana/levana so določili s standardnimi analiznimi metodami. Izguba mase gomoljev se je povečala z 0,85 % po 30 dneh na 9,20 % po 180 dneh. Vsebnost saharoze je padla z 18,30 % ob pobiranju na 17,17 % po 180 dneh, kar ustreza relativni izgubi saharoze 6,17 %. Vsebnost kalija se je povečal s 3,85 na 5,31 mmol 100 g⁻¹, natrija z 0,48 na 1,03 mmol 100 g⁻¹ in α -amino dušikovih spojin z 11,8 na 27,8 mg 100 g⁻¹. Kopičenje dekstrana/levana je ostalo majhno v prvih 90 dneh, vendar se je po 120 dneh močno povečalo in doseglo 3,31 % do 180. dneva. Rezultati kažejo, da shranjevanje v poljskih jamah na prostem ne sme presegati 120 dni.

Ključne besede: sladkorna pesa, poljske jame, dolgotrajno skladiščenje, vsebnost saharoze, dekstran, levan, tehnološka kakovost, α -amino dušik

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1 INTRODUCTION

An important stage in modern agricultural production is stable storage of produce under controlled conditions without quality loss until it moves to the next stage of the value chain. The choice of storage systems is crucial, considering both storage costs per yield unit and the degree of quality deterioration under existing conditions (Kleuker & Hoffmann, 2022).

In Ukraine, as in Canada, the USA, and Northern Europe, post-harvest sugar beet (*Beta vulgaris* L. ssp. *vulgaris* var. *altissima* Döll.) storage is carried out in the field, specifically in clamps. Harvest usually finishes in November, but processing enterprises may operate until the end of January. In Western Europe, sugar factories often operate up to three months after harvest (Huijbregts et al., 2013). Therefore, the assessment of both quantitative and qualitative losses of sugar beet during storage is economically important.

The amount of white sugar extractable from stored beets largely depends on raw material quality, which is the highest when roots contain a high sucrose concentration and low levels of impurities. The main molasses-forming substances are potassium, sodium, and α -amino nitrogen, which increase sucrose losses to molasses. Additionally, invert sugars (glucose and fructose) produced by sucrose breakdown contribute to color formation during crystallization, reduce juice filtration, and lower sugar extraction efficiency (Hoffmann, 2010). In addition to storage conditions, the technological quality of sugar beet roots is strongly influenced by pre-storage agronomic factors, particularly harvest timing. Under the conditions of the Western Forest-Steppe of Ukraine, harvest time has been shown to significantly affect root yield and technological quality parameters, indicating that the initial quality of roots entering storage is largely predetermined before clamping (Kyselov et al., 2026).

Researchers note that most losses during long-term storage result from active root respiration, which causes 50–80 % of sucrose losses (Kandel et al., 2024). Sugar beet roots are also susceptible to mechanical damage during harvest, loading, unloading, and reloading, which facilitates microbial infection. Elevated temperature and moisture within clamps stimulate microbial activity, accelerating degradation and root softening (Campbell & Klotz, 2006). Thus, storage losses depend on both root quality and environmental conditions.

There is no unified definition of “long-term storage” of sugar beet in the literature. English (2023) proposed to interpret it as storage under physiological stability – when one or more physiological parameters remain constant despite external factors (Leibel et al., 2016). For sugar beet storage, a period beyond two weeks is often

considered long-term, corresponding to wound healing and reduced respiration intensity. This aligns with the > 15-day definition provided by European researchers (Legrand & Wauters, 2012).

Effective sugar beet storage depends on ensuring root quality before clamping. Healthy, pathogen-free roots demonstrate significantly better storability and lower sucrose losses than roots infected with rot pathogens. For example, Strausbaugh et al. (2011) reported that roots infected with *Rhizoctonia solani* J.G.Kühn. and bacterial pathogens experienced accelerated rot development and significant sugar losses during storage.

Another important factor is optimal harvesting with minimal mechanical injuries. Huijbregts et al. (2013) emphasized that pre-harvest plant health, including absence of stress and high phytosanitary security, determines the ability of beets to maintain high sucrose content and low respiration during extended storage. Hence, compliance with agronomic practices that sustain plant health and proper harvesting are key prerequisites for minimizing storage losses.

The characteristics of optimal storage require clear definition and standardization. High sucrose content and low levels of invert sugars (glucose, fructose), microbial polysaccharides (especially dextran and levan), and non-sugar solubles such as α -amino nitrogen, sodium, and potassium are considered the main quality criteria (Hoffmann, 2010; Liebe & Varrelmann, 2016). During storage, invert sugars are formed by sucrose hydrolysis, leading not only to direct sucrose loss but also to impaired crystallization and reduced white sugar yield (Dutton & Huijbregts, 2006).

The term “storability” is used in scientific practice to describe the ability of roots to retain quality. Quality decline during storage is typically expressed as reduced sucrose and increased impurities that worsen extraction efficiency (Kenter & Hoffmann, 2009; English, 2023). The main reasons for losses include respiration, molding, and root rot (Klotz et al., 2006; Liebe & Varrelmann, 2014; Liebe et al., 2016; Fugate et al., 2024).

Some studies indeed report that high-sucrose hybrids sometimes exhibit better storability (Hoffmann et al., 2018), possibly linked to anatomical root traits such as thicker cell walls, cambial ring number, and parenchymal cell size. However, as emphasized by Liebe & Varrelmann (2016), sucrose content alone is not decisive for storability, which depends on a complex of physiological, biochemical, and microbial traits.

The aim of this research was a comprehensive evaluation of mass, sucrose, and technological quality losses of sugar beet during long-term storage in field clamps under production conditions, and determination of the

critical storage period to develop recommendations for minimizing losses.

2 MATERIALS AND METHODS

2.1 EXPERIMENTAL SITE AND PLANT MATERIAL

The study was conducted under production conditions at PE “Zakhidnyi Buh” (Lviv Region, Western Ukraine) during the 2024–2025 storage seasons. Sugar beet roots (*Beta vulgaris* L.) from two commercial hybrids ‘Strube Augusto’ and ‘KWS Koncertina’ were harvested in late October under standard production practices. Since the study was designed to evaluate storage losses under commercial field clamp-storage conditions, roots from these hybrids were stored as a commercial production batch rather than as separate genotype treatments. Harvested roots were placed in field clamps covered with protective layers of soil and nonwoven material to simulate typical on-farm storage.

2.2 EXPERIMENTAL DESIGN

Storage dynamics were studied over 180 days (November–April) with five sampling dates: immediately after harvest, and at 60, 90, 120, and 180 days. For each sampling point, five replicate samples of 25 kg each were collected from different layers of the clamp (upper, middle, lower).

2.3 MEASUREMENTS

Mass losses were determined gravimetrically by comparing the fresh mass of sugar beet root tubers at harvest with their subsequent mass recorded at each sampling date during storage. Sucrose concentration in sugar beet root tubers was measured according to the ICUMSA polarimetric method GS6/7–4 (ICUMSA, 2011). For this analysis, representative tuber samples were cleaned, homogenized into beet brei, and a defined subsample was extracted using the prescribed extraction solution. The extract was clarified to remove suspended particles and optically interfering compounds and then filtered to obtain a clear filtrate. Polarimetric measurements were performed using a calibrated polarimeter under controlled temperature conditions. Sucrose concentration was calculated from the optical rotation of the clarified filtrate, taking into account sample mass, extract volume, tube length, temperature correction, and the calculation factors specified in the ICUMSA GS6/7–4 method. The results were expressed as percentage of sucrose in fresh root mass (% FM), and all analyses were performed at least in duplicate. Invert sugars, including glucose and fruc-

tose, and polysaccharides, including dextran and levan, were determined enzymatically according to Liebe and Varrelmann (2016), and the results were expressed on a fresh mass basis. Impurity content, represented by potassium (K), sodium (Na), and α -amino nitrogen, was measured using ion-selective electrodes and the OPA method, respectively, as described by Hoffmann (2010). The concentrations of K and Na were expressed as mmol 100 g⁻¹ dry matter basis, while α -amino nitrogen was expressed as mg 100 g⁻¹ dry matter basis.

2.4 STATISTICAL ANALYSIS

All data were analyzed using ANOVA. Differences between treatments and time points were assessed using Fisher’s Least Significant Difference (LSD) test at $p < 0.05$. Statistical analyses were performed with MS Excel (Ott, R. & Longnecker, 2015).

3 RESULTS AND DISCUSSION

3.1 DYNAMICS OF ROOT TUBER MASS LOSS DURING STORAGE

During commercial long-term storage of sugar beet, the total sugar loss may range between 1–10 % compared with the parameters recorded at harvest. However, in some cases extreme losses are observed, when the product becomes unsuitable for processing.

It should be noted that root rots are one of the main causes of significant yield losses during clamp storage of sugar beet, as well as losses due to the formation of invert sugar in the roots (Klotz et al., 2008; Liebe and Varrelmann, 2016).

After the sugar beet harvest on October 20, 2024, samples consisting of five roots from each excavation were collected and submitted for further laboratory analysis. The study was carried out with five replications.

Root mass loss increased steadily with storage duration (Table 1). During the first 60 days, cumulative losses remained relatively low and did not exceed 2.15 %, indicating a phase of moderate respiration and limited moisture evaporation. By day 90, cumulative mass loss reached 3.65 %, and by day 120 it rose to 5.10 %. The most pronounced increase occurred in the late storage period, when cumulative losses reached 7.25 % after 150 days and 9.20 % after 180 days.

These results indicate that the first two to three months of storage remained relatively stable under the studied commercial conditions, whereas the transition to late winter and early spring was accompanied by accelerated deterioration. This pattern agrees with reports

Table 1: Physical mass loss of sugar beet root tubers during long-term storage (2024–2025 season)

Storage duration (days)	Tuber mass loss (%) $\pm$ SE
0	0.00 $\pm$ 0.00
30	0.85 $\pm$ 0.07
60	2.15 $\pm$ 0.11
90	3.65 $\pm$ 0.14
120	5.10 $\pm$ 0.16
150	7.25 $\pm$ 0.20
180	9.20 $\pm$ 0.24

Note: Values are means of five replications; SE – standard error.

from Northern and Northwestern Europe, where outdoor clamp storage typically remains acceptable during the first half of winter, but mass loss increases sharply in response to rising temperature and increased root respiration in spring (Huijbregts, 2008a; Olsson *et al.*, 2011; Legrand & Wauters, 2012).

The progressive increase in root mass loss reflects the cumulative impact of respiration, evaporative water loss, and tissue degradation. Although the roots remained physically storable throughout the study period, the magnitude of losses recorded after 120 days indicates a transition from acceptable storage to economically disadvantageous storage.

3.2 CHANGES IN SUCROSE CONTENT AND SUCROSE LOSS

The results confirm that under optimal storage conditions, mass losses can be maintained at an acceptable level; however, prolonged storage beyond five months significantly reduces both root biomass and the potential sucrose concentration. Nevertheless, mass loss alone cannot serve as a sufficient indicator of storage efficiency; therefore, the next stage of research focused on analysing sucrose content losses (Table 2).

Sucrose content declined gradually during the storage period (Table 2). The initial concentration at harvest was 18.30 %, corresponding to high-quality raw material. During the first 60 days, the decrease was limited, and sucrose content remained above 18.0 %. However, from 90 days onward, the decline became more pronounced. By day 150, sucrose content had decreased to 17.35 %, and by day 180 it fell to 17.17 %, corresponding to a relative loss of 6.17 % compared with the initial value.

The temporal pattern of sucrose depletion closely reflected the progression of physiological ageing and storage stress. Low losses in early storage indicate restrained respiration and limited metabolic disruption. In

Table 2: Sucrose content loss of sugar beet roots during long-term storage (2024–2025 season)

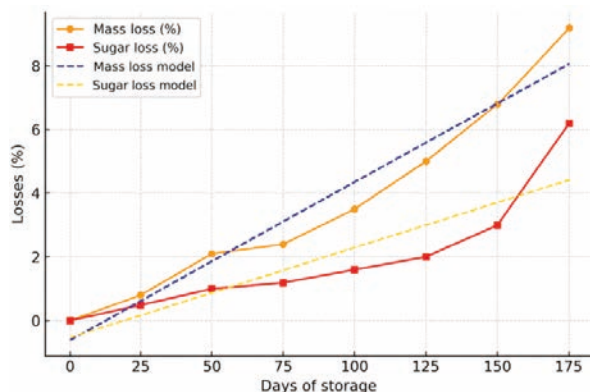
Storage duration (days)	Sucrose content (% FW) $\pm$ SE	Relative sucrose loss (%)
0	18.30 $\pm$ 0.08	0.00
30	18.23 $\pm$ 0.09	0.38
60	18.08 $\pm$ 0.10	1.20
90	17.92 $\pm$ 0.11	2.08
120	17.71 $\pm$ 0.12	3.22
150	17.35 $\pm$ 0.13	5.19
180	17.17 $\pm$ 0.14	6.17

Note: Values are means of five replications; SE – standard error.

contrast, the stronger reduction observed after 120 days suggests accelerated catabolism and higher vulnerability to microbial processes. Similar biphasic dynamics have been described in commercial sugar beet storage, where the early storage period is relatively stable, followed by a late phase of intensified sugar depletion (Kenter & Hoffmann, 2009; Kandel *et al.*, 2024).

The summarized dynamics of mass and sucrose losses are presented in Figure 1. Based on these results, the end of February can be regarded as the maximum allowable storage duration when considering both parameters. After mid-February, the rate of deterioration increased sharply: by mid-April, root mass had declined by more than 9 %, while sucrose content decreased by over 6 %, both of which are critical thresholds for processing. The main factors driving these losses were rising temperatures, increased microbial activity, and enhanced root respiration. Therefore, the optimal storage period for sugar beet in outdoor clamps should be restricted to 3–3.5 months after harvest.

The practical significance of these changes is substan-

**Figure 1:** Dynamics of mass loss and sucrose reduction in sugar beet roots during storage

tial. Even when roots maintain acceptable physical appearance, progressive sucrose depletion directly reduces the recoverable sugar yield. Therefore, evaluation of storage efficiency should account not only for mass retention but also for preservation of sucrose concentration.

3.3 ACCUMULATION OF DEXTRAN AND LEVAN DURING STORAGE

The next parameter for assessing the suitability of sugar beet roots during storage was the presence of bacterial polysaccharides changes such as dextran and levan (Table 3). Dextran is a high-molecular-weight glucan synthesized by bacteria, predominantly *Leuconostoc* spp., during the breakdown of sucrose. Levan is a fructan synthesized by bacteria such as *Pseudomonas* and *Bacillus*, or by certain fungi, in the presence of sucrose (Liebe & Varrelmann, 2016; Hoffmann et al., 2018). Elevated concentrations of dextran (> 3 %) lead to impaired juice filtration, increased viscosity, and reduced sugar recovery.

The content of microbial polysaccharides remained negligible during the first 90 days of storage, but increased markedly during the later stages (Table 3). No measurable accumulation was detected at 0 and 30 days, while only trace amounts were recorded by day 60. At day 90, total dextran/levan content reached 0.18 %, still within a technologically safe range. By day 120, accumulation increased to 0.46 %, with levan being the dominant component. A much sharper rise was observed after 150 days, when total content reached 1.72 %, and especially after 180 days, when dextran/levan content rose to 3.31 %, with dextran predominating.

This shift from minor levan formation in the intermediate storage period to dominant dextran accumulation in late storage is important for technological interpretation. Levan is often associated with early microbial activity under relatively cooler conditions, whereas dextran accumulation is more closely linked with intensified bacterial

Table 3: Dextran and levan accumulation in sugar beet roots during long-term field clamp storage (2024–2025)

Storage duration (days)	Dextran/levan content (%) ± SE	Dominant fraction
0	0.00 ± 0.00	Not detected
30	0.00 ± 0.00	Not detected
60	0.05 ± 0.01	Trace levan
90	0.18 ± 0.03	Levan
120	0.46 ± 0.05	Levan
150	1.72 ± 0.12	Dextran
180	3.31 ± 0.18	Dextran

Note: Values are means of five replications; SE – standard error.

degradation under warmer and less stable storage conditions. The dextran concentrations recorded in the late storage period in our study are consistent with technological thresholds associated with reduced sugar recovery, stronger color formation, and lower filterability of processing juice (Hoffmann, 2010; Dutton & Huijbregts, 2006).

The results confirm that microbial deterioration became technologically relevant mainly after 120 days of storage and became critical by day 180. Thus, dextran/levan formation acted as a sensitive indicator of the transition from physiologically controlled storage to microbiologically unstable storage.

3.4 CHANGES IN TECHNOLOGICAL IMPURITIES DURING STORAGE

Potassium, sodium, and α-amino nitrogen increased progressively with storage duration (Table 4). At harvest, the concentrations of these compounds were relatively low, indicating favorable processing quality. However, as

Table 4: Changes in technological impurities of sugar beet roots during long-term field clamp storage, expressed on a dry matter basis (2024–2025)

Storage duration (days)	K (mmol 100 g ⁻¹) ± SE	Na (mmol 100 g ⁻¹) ± SE	α-amino N (mg 100 g ⁻¹) ± SE
0	3.85 ± 0.06	0.48 ± 0.02	11.8 ± 0.5
30	3.92 ± 0.07	0.50 ± 0.02	12.4 ± 0.5
60	4.05 ± 0.07	0.56 ± 0.03	13.9 ± 0.6
90	4.26 ± 0.08	0.63 ± 0.03	15.7 ± 0.7
120	4.52 ± 0.09	0.74 ± 0.04	18.6 ± 0.8
150	4.88 ± 0.10	0.88 ± 0.04	22.4 ± 0.9
180	5.31 ± 0.11	1.03 ± 0.05	27.8 ± 1.1

storage continued, all three impurities accumulated, particularly after 90–120 days.

Potassium increased from 3.85 to 5.31 mmol 100 g⁻¹ over the 180-day storage period. Sodium increased from 0.48 to 1.03 mmol 100 g⁻¹, while α -amino nitrogen rose from 11.8 to 27.8 mg 100 g⁻¹. The strongest increase was observed during the late storage period, coinciding with accelerated root mass loss, stronger sucrose depletion, and increased dextran accumulation.

The increase in K, Na, and α -amino N has direct technological significance because these are molasses-forming substances that reduce sugar extraction efficiency and increase the amount of sucrose lost to molasses. Therefore, even if root mass losses remain within operationally tolerable limits, the accumulation of these impurities may render late-stored roots less suitable for efficient industrial processing.

This finding strengthens the practical conclusion of the study: the threshold of acceptable storage should be defined not only by fresh mass preservation, but also by technological purity

3.5 CORRELATION ANALYSIS AMONG STORAGE-RELATED TRAITS

Pearson correlation analysis showed strong positive relationships among storage duration, root mass loss, sucrose loss, impurity accumulation, and dextran/levan formation (Table 5). Storage duration was very strongly correlated with root mass loss ($r = 0.991$), sucrose loss ($r = 0.981$), potassium ($r = 0.968$), sodium ($r = 0.970$), and α -amino nitrogen ($r = 0.957$). Sucrose content was negatively correlated with all indicators of deterioration, especially root mass loss ($r = -0.996$), sodium ($r = -0.995$), and sucrose loss ($r = -1.000$ by definition of inverse expression).

Dextran/levan content was positively correlated

with root mass loss ($r = 0.903$), sucrose loss ($r = 0.864$), sodium ($r = 0.943$), and α -amino nitrogen ($r = 0.960$), indicating that microbial polysaccharide accumulation intensified in parallel with biochemical deterioration of stored roots.

The correlation structure obtained in the present study confirms that sugar beet deterioration during long-term storage is a multidimensional process in which quantitative losses, biochemical changes, and technological degradation progress simultaneously. This interpretation agrees with the broader literature indicating that post-harvest losses are not determined by a single factor, but arise from the interaction of respiration, tissue degradation, microbial activity, and impurity accumulation during storage (Klotz *et al.*, 2008; Liebe & Varrelmann, 2016; Kandel *et al.*, 2024). Consequently, integrated assessment of storage-related traits provides a more realistic basis for defining the safe storage horizon than evaluation of fresh mass loss alone.

The correlation structure confirms that storage deterioration in sugar beet is multidimensional and tightly interconnected. Root mass loss alone is insufficient to characterize storage performance, because technological deterioration may intensify even before catastrophic physical spoilage occurs. Therefore, integrated interpretation of quantitative and biochemical indicators provides a more reliable basis for defining the acceptable storage horizon.

3.6 GENERAL INTERPRETATION AND PRACTICAL IMPLICATIONS

The combined analysis of mass loss, sucrose depletion, impurity accumulation, and dextran/levan formation clearly indicates that the first 90–120 days of storage represented a relatively stable phase under the conditions of this study. Beyond that point, however, the rate of deteriora-

Table 5: Pearson correlation coefficients among storage duration and quality traits of sugar beet roots

Trait	Storage duration	Mass loss	Sucrose content	Sucrose loss	Dextran/levan	K	Na	α -amino N
Storage duration	1.000	0.991	-0.981	0.981	0.845	0.968	0.970	0.957
Mass loss	0.991	1.000	-0.996	0.996	0.903	0.992	0.993	0.985
Sucrose content	-0.981	-0.996	1.000	-1.000	-0.864	-0.990	-0.995	-0.987
Sucrose loss	0.981	0.996	-1.000	1.000	0.864	0.990	0.995	0.987
Dextran/levan	0.845	0.903	-0.864	0.864	1.000	0.934	0.943	0.960
K	0.968	0.992	-0.990	0.990	0.934	1.000	1.000	0.999
Na	0.970	0.993	-0.995	0.995	0.943	1.000	1.000	0.998
α -amino N	0.957	0.985	-0.987	0.987	0.960	0.999	0.998	1.000

tion increased markedly. In practical terms, storage up to approximately four months after harvest remained conditionally acceptable, whereas storage beyond this period led to rapid quality decline.

A crucial interpretive context for these results is the quality of raw material at storage entry. This interpretation is also supported by previous evidence from the same agroecological region showing that harvest timing substantially affects root yield and technological quality before storage, thereby influencing the initial quality status of roots entering the post-harvest storage chain (Kyselov et al., 2026). The roots examined in this study entered storage with high initial sucrose content and without obvious signs of disease, which indicates that the sharp post-February acceleration of losses was primarily associated with hydrothermal and microbiological factors rather than poor initial quality. This interpretation is consistent with reports showing that mechanical injuries during lifting, loading, and rehandling create entry points for microorganisms, intensify respiration, and accelerate storage losses (Klotz et al., 2006; Campbell & Klotz, 2006). Even when healthy roots are placed into storage, prolonged residence in outdoor clamps may progressively shift the system toward a high-risk condition due to internal heat accumulation and localized microbial “hot spots” (Liebe & Varrelmann, 2014; Liebe et al., 2016).

The operational interpretation of long-term storage in the present study, namely storage extending beyond 90–120 days under commercial clamp conditions, is consistent with European concepts of prolonged sugar beet storage as a period in which physiological stability gradually gives way to intensified quality decline (Legrand & Wauters, 2012; English, 2023). In this regard, the end of February can be considered the practical and economically feasible horizon for storage under the studied conditions, since further prolongation sharply increases the risk

of losses not only in fresh mass and sucrose, but also in technological processability.

Principal component analysis showed that the first principal component (PC1) explained 97.94 % of the total variation, whereas the second principal component (PC2) explained only 1.91 %. Thus, the variation among storage periods was determined mainly by a single dominant gradient associated with progressive deterioration of sugar beet roots during storage (Fig. 2).

The positive side of PC1 was strongly associated with root mass loss, relative sucrose loss, dextran/levan accumulation, potassium, sodium, and α -amino nitrogen, whereas sucrose content was located on the negative side of PC1. This indicates that increasing storage duration shifted the samples from a state of high technological quality toward a state characterized by quantitative and biochemical deterioration.

The biplot clearly separated the storage periods into three groups. The samples collected at 0–60 days were located on the negative side of PC1 and were associated with high sucrose content and minimal losses, indicating relatively stable storage conditions. The 90–120 day samples occupied an intermediate position and reflected the transition phase, when the first signs of technological deterioration became evident. The 150–180 day samples were positioned on the strongly positive side of PC1 and were closely associated with high mass loss, sucrose depletion, impurity accumulation, and microbial polysaccharide formation, confirming that late storage corresponded to the phase of critical quality decline.

PC2 contributed little to the total variation, but it slightly distinguished late storage periods according to dextran/levan accumulation, suggesting that microbial polysaccharide formation represented a secondary, but technologically important, source of variation superimposed on the general storage deterioration gradient.

Overall, the PCA biplot confirmed that long-term clamp storage of sugar beet is governed by a strong integrated deterioration axis, and that storage beyond approximately 120 days leads to a rapid transition toward poor technological suitability of roots for processing.

4 CONCLUSIONS

The study demonstrated that long-term field clamp storage of sugar beet under commercial conditions caused progressive deterioration in both quantitative and technological quality indicators of the roots.

Root mass loss increased from 0.85 % after 30 days to 9.20 % after 180 days, while sucrose content decreased from 18.30 % at harvest to 17.17 % after 180 days, corresponding to a relative loss of 6.17 %. These changes indi-

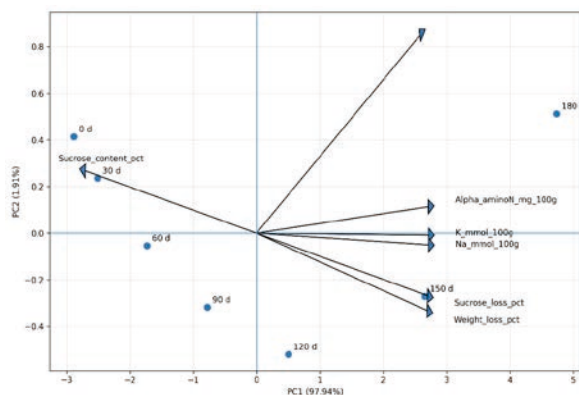


Figure 2: PCA biplot of storage duration and technological quality traits of sugar beet roots during long-term field clamp storage.

cate that prolonged storage resulted in substantial reduction of recoverable sugar potential.

A marked increase in technological impurities was observed during storage. Potassium rose from 3.85 to 5.31 mmol 100 g⁻¹, sodium from 0.48 to 1.03 mmol 100 g⁻¹, and α -amino nitrogen from 11.8 to 27.8 mg 100 g⁻¹. This confirms that late storage not only reduces sucrose concentration, but also worsens the industrial processing quality of the roots.

Dextran and levan accumulation remained negligible during the first 90 days, but increased sharply after 120 days. By day 180, total dextran/levan content reached 3.31 %, with dextran predominating, indicating microbiologically unstable storage and a high risk of processing complications.

Correlation analysis confirmed strong positive relationships between storage duration and all major indicators of root deterioration, including mass loss, sucrose loss, impurity accumulation, and microbial polysaccharide formation.

Under the studied conditions, the technologically and economically acceptable storage duration of sugar beet in outdoor clamps should not exceed approximately 120 days, while storage beyond the end of February substantially increases the risk of quality loss and reduced factory processing efficiency.

Data Availability

All data generated and analyzed in this study are original and presented in this manuscript

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