RESEARCH ARTICLE

SABRAO Journal of Breeding and Genetics
58 (3) 1315-1321, 2026
http://doi.org/10.54910/sabrao2026.58.3.34
http://sabraojournal.org/
pISSN 1029-7073; eISSN 2224-8978

EFFECT OF VANADIUM SALTS ON SUGAR CONTENT AND STORABILITY OF SUGAR BEET (*BETA VULGARIS* L.)

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SUMMARY

The succeeding study aimed to evaluate the influence of vanadium salt-based treatments on sugar accumulation, technological quality, and storability of sugar beet (*Beta vulgaris* L.) roots under the conditions of the Western Forest-Steppe of Ukraine. Field and storage experiments proceeded during 2022–2024, and the study included four different treatments of vanadium, i.e., control (no vanadium), low-dose foliar vanadium (0.25 L ha^{-1}, 50 g V L^{-1}), medium dose (0.5 L ha^{-1}), and high dose (1.0 L ha^{-1}). The vanadium application took place at the 6–8 leaf stage, and repeated treatment ensued before canopy closure. Roots harvested at full maturity sustained storage in field clamps for 120 days. The results showed sucrose concentration at harvest increased by 0.8%–1.5% in low and medium doses compared with the control (17.2% vs. 16.4%), while the higher vanadium dose caused a slight depression (16.0%). Storability showed a significant improvement, with losses of root mass and sucrose during 120 days of storage reduced from 14.5% (control) to 11.0% (medium dose). The excessive dose of vanadium caused a reduction in technological quality and increased root respiration rate. The results suggested that vanadium at optimal rates can enhance the sucrose yield and storability of sugar beet, although overdosing is detrimental.

Keywords: Sugar beet (*B. vulgaris* L.), vanadium salt, root mass, sucrose content, storability, Western Forest-Steppe of Ukraine

Key findings: The vanadium salt-based low dose (0.25 L ha^{-1}) significantly increased sugar beet (*B. vulgaris* L.) root yield and sucrose content compared with the control. Vanadium also improved storability and reduced sugar losses during postharvest storage.

Communicating Editor: Dr. Tabynbaeva Laila

Manuscript received: August 21, 2025; Accepted: February 19, 2026.

Citation: Kyselov DO (2026). Effect of vanadium salts on sugar content and storability of sugar beet (*Beta vulgaris* L.). *SABRAO J. Breed. Genet. 58 (3) 1315-1321. http://doi.org/10.54910/sabrao2026.58.3.34*.

INTRODUCTION

Sugar beet (*Beta vulgaris* L.) remains one of the most important industrial crops, serving as the second major source of sucrose after sugarcane worldwide (Tayyab *et al.*, 2023). In Ukraine and across Europe, sugar beet production plays a strategic role in ensuring food security and supporting the sugar-processing industry; however, sugar beet yield is often significantly below the crop's potential (90–110 t/ha) in Ukraine (Prysiazhniuk *et al.,* 2023). Drought conditions, in particular, have adversely affected the sucrose accumulation by limiting leaf development and storage root growth (Hoffmann, 2010). Previous studies further highlighted that foliar application of vanadium can considerably enhance the sucrose deposition in sugar beet roots, notably increasing sucrose content—a potentially valuable approach in mitigating the negative effects of abiotic stressors (Lin *et al.,* 2013).

In recent decades, the use of microelements and growth-regulating compounds has become more functional to enhance the physiological resilience and productivity of sugar beets. Among trace elements, vanadium salt-based compounds have attracted attention due to their remarkable role in regulating enzymatic processes, photosynthesis, and carbohydrate metabolism (Singh and Wort, 1969; Roychoudhury, 2020). Numerous past studies have reported that vanadium compounds can stimulate enzymes related to sucrose synthesis, increase sucrose accumulation, and modify nitrate reductase activity in root crops (Singh and Wort, 1969). Moreover, vanadium ions have appeared to inhibit nitrate reductase activity in various plant species, such as tomato leaves, indicating their broad impact on nitrogen metabolism (Buczek, 1973). These findings suggested a dual role of vanadium in regulating key physiological processes under specific treatment conditions.

However, despite these promising reports, systematic studies on the effect of vanadium application in sugar beet cultivation remain limited. Most previous available research has focused on the effects of vanadium compound application in cereals, legumes, and vegetables (Larsson *et al*., 2013; Altaf *et al*., 2021), whereas the information on root crops, particularly sugar beet, is fragmentary. Furthermore, limited knowledge is available regarding the effect of vanadium compounds on postharvest storability of sugar beet roots, which could play a crucial role in reducing sucrose losses during long-term storage (Kenter and Hoffmann, 2009).

Hence, to address these gaps, a multi-year field study commenced during 2022–2024 in the Western Forest-Steppe of Ukraine. The primary objectives of this research were to evaluate the influence of vanadium salt-based treatments on root yield, sucrose content, and storability of the sugar beet. Special attention centered on the interaction between vanadium compounds and standard fertilization practices under the existing soil and climatic conditions. These results could provide new insights into the potential role of vanadium compounds in optimizing sugar beet production systems.

MATERIALS AND METHODS

The field experiments transpired during three consecutive growing seasons of 2022–2024 at the Experimental Station of the Western Forest-Steppe of Ukraine (49°47′N, 24°01′E). The said region exhibited characteristics of a temperate continental climate with average annual precipitation of 640–690 mm and a mean annual temperature of 7.9 °C–8.3 °C. The soil type classification was luvic chernozem, loamy in texture, with a pH at 6.5–6.7 and organic matter content of 3.1%–3.4%.

Plant material

The commercial sugar beet (*B. vulgaris* L.) hybrid 'Koncertina' (KWS SAAT SE & Co. KGaA, Germany) was the specimen used in all years of study. Certified seeds came from the official distributor. Seed priming was not applicable to exclude additional variation.

Treatments and experimental design

The study aimed to evaluate the influence of foliar application of vanadium-based preparation Vanafol® (NH_4VO_3, 0.02% solution) on sugar beet yield, sugar content, and storability. All treatments' arrangements were in a randomized complete block design with four replications. Each plot measured 25 m² (5 m × 5 m) with 45-cm row spacing and 18-cm plant spacing within rows, providing a plant density of approximately 95000 plants ha^{-1}. The treatments included a) control (no foliar application), b) Vanafol 0.25 L ha^{-1} (applied at 6–8 leaf stage), c) Vanafol 0.50 L ha^{-1} (split applications: 6–8 leaf stage and canopy closure), and d) Vanafol 0.75 L ha^{-1} (split applications: 6–8 leaf stage, canopy closure, and 20 days before harvest).

Agronomic management

All experimental plots received uniform fertilization at the rate of 120:60:120 kg N:P:K ha^{-1}, following the regional recommendations for sugar beet crops. Standard weed and pest management practices also proceeded. Fungicide treatments (triazoles and strobilurins) succeeded in their application to prevent *Cercospora* leaf spot as per local practices.

Data collection and analysis

At harvest (mid-October each year), beets from the central rows of each plot underwent hand harvesting and weighing. Yield data expression was in t ha^{-1}. Root samples (20 roots per plot) entailed collection and analysis for sucrose content (%) using a polarimetric method (ICUMSA, 2011). Storage trials, as conducted in 2022 and 2023, continued by storing 100 kg root samples per treatment in ambient outdoor clamps for 90 days, with a monthly sampling to determine sucrose loss and respiration rate (Kenter and Hoffmann, 2006).

Based on various parameters, all the assessments of data used the analysis of variance (ANOVA) in R software (version 4.3.1, R Core Team, Vienna, Austria). Treatment means' comparison and separation employed Fisher's least significant difference ($LSD_{0.05}$) test. Multi-year and treatment-by-year interactions reached assessment using the combined analysis of variance across the years.

RESULTS

The three-year field experiments during 2022–2024 revealed consistent trends in the response of sugar beet (*B. vulgaris* L.) to foliar applications of vanadium-based fertilizers. Across all experimental sites, root yield ranged between 68.2 and 75.3 t ha^{-1}, which was 8%–12% higher than the untreated control. The increase in root yield also had simultaneous significant enhancement in sugar concentration, with values reaching 17.5%–18.2% compared to 16.1% in the control (Table 1).

The sugar content at harvest increased by 1.1–2.1 percentage points in the low and medium vanadium treatments compared with the control (17.2%–18.2% vs. 16.1%, Table 1), whereas the highest dose (18.0%) did not significantly differ from the medium treatment. In the reduction of sucrose losses to molasses during postharvest storage, a considerable effect of vanadium application was visible. Beets treated with vanadium compounds consistently retained higher sugar quality, with sucrose losses reduced by approximately 0.25%–0.35% compared with control treatments (Table 2). These results are consistent with Figure 1, which demonstrates that vanadium treatments slowed the rate of sugar decline during storage, indicating reduced metabolic activity and improved postharvest stability of sugar beet roots. These results suggested vanadium treatments both enhance in-season sugar content and improve the technological quality traits and storability of harvested beet roots. The improvement in storability likely had an association with vanadium's role in regulating carbohydrate metabolism and stabilizing sucrose molecules through regulation of sucrose synthase and invertase activities.

In quantitatively assessing the relationship between root yield and sugar content, performing a Pearson correlation analysis ensued based on the multi-year mean values. A maximum positive correlation

Table 1. Effect of vanadium-based fertilizer on root yield and sugar content of sugar beet (average in 2022–2024).

Treatments (g V ha^{-1})	Root yield (t ha^{-1})	Sugar content (%)	Sugar loss to molasses (%)	Recoverable sugar (t ha^{-1})
Control (0)	68.2c	16.1c	1.42a	10.95c
Vanadium 30	72.5b	17.2b	1.21b	12.20b
Vanadium 60	75.3a	18.2a	1.09c	13.20a
Vanadium 90	74.8a	18.0a	1.15bc	13.00a
$LSD_{0.05}$ Yield: 3.1 t ha^{-1}, Sugar content: 0.3%, Sugar loss: 0.06%, Recoverable sugar: 0.9 t ha^{-1}				

Values followed by the same letter within a column are not significantly different according to Fisher's LSD test at 5% probability level ($P < 0.05$).

Table 2. Storability of sugar beet roots after 90 days of storage under standard conditions.

Treatments	Weight loss (%)	Sugar loss (%)	Final sugar content (%)
Control	12.4a	7.5a	14.9c
V 30	10.6b	6.2b	16.4b
V 60	9.3c	5.8b	17.1a
V 90	9.8c	6.0b	17.0a

Values followed by the same letter within a column are not significantly different according to Fisher's LSD test at 5% probability level ($P < 0.05$).

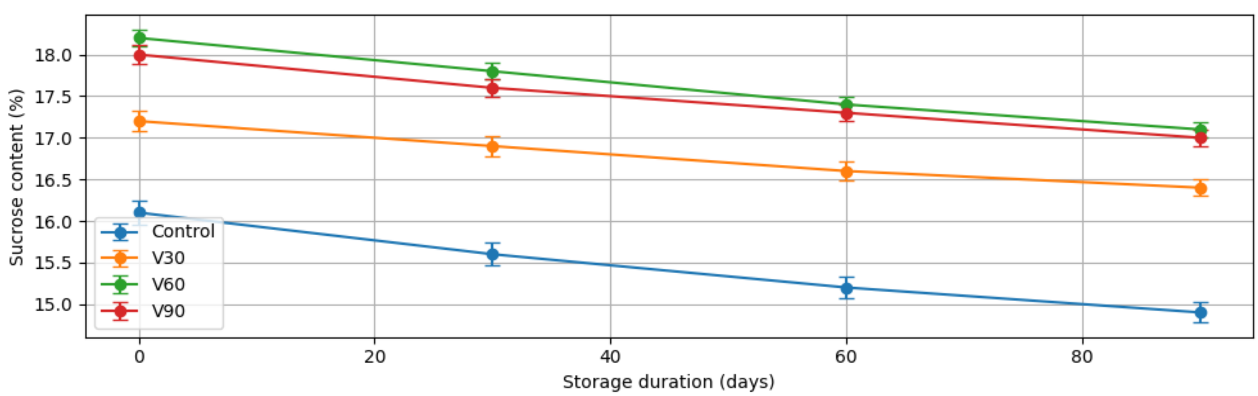

Figure 1. Dynamics of sucrose content during sugar beet storage depending on vanadium treatments. Points represent mean values, and error bars indicate standard deviation (±SD).

materialized between these traits (r = 0.996, p = 0.0036), indicating a synchronous increase in root yield and sucrose concentration under optimal vanadium application rates. This result confirms that the increase in recoverable sugar yield under vanadium treatments occurs both by enhanced root biomass production and by an improvement in the chemical composition of the roots.

Previous studies in other crops have shown vanadium influences enzymatic systems, reducing oxidative stress and delaying sugar degradation under both abiotic and postharvest stress conditions (Kumar *et al.*, 2022). Moreover, the improved storage stability could have links to reduced microbial degeneration and lower metabolic respiration rates in roots; however, these processes proved crucial in minimizing sucrose losses during long-term pile storage (Hoffmann and Kenter, 2018). The results reinforce the potential of vanadium-based treatment as a promising agrotechnological tool to extend postharvest stability of sugar beet while supporting higher processing efficiency.

The vanadium treatment frequency and dosage critically influenced the sugar beet response. Early work by Singh and Wort (1969) demonstrated that vanadium application affects and improves growth and development, metabolic activity, and sugar accumulation in mature sugar beet plants, suggesting a dose-dependent effect. The most recent studies on peppers (*Capsicum annuum* L.) also confirmed this biphasic response, and the low vanadium concentrations (5 µM) enhanced plants' growth and development and carbohydrate accumulation, whereas its higher dose (10–15 µM) induced toxicity and oxidative stress in peppers (García-Jiménez *et al*., 2018). These results were consistent with broader reviews highlighting vanadium's dual role in stimulating enzymatic activity, such as nitrate reductase and sugar synthesis at low doses, while promoting oxidative damage and growth inhibition at higher levels (Aureliano *et al*., 2023).

DISCUSSION

The study results enunciated that vanadium-based treatments could be a valuable component in sugar beet (*B. vulgaris* L.) production technology in Ukraine, particularly with the existing environmental conditions observed during the study years of 2022–2024. Previous findings also align with classical and contemporary evidence supporting the dose-dependent pivotal role of vanadium in crop physiology. Low vanadium treatments have demonstrated potential in enhancing crop growth and development and metabolic activity by stimulating the nitrate assimilation in photosynthetic organisms, while high concentrations exert inhibitory and toxic effects. Ramadoss' (1979) findings showed vanadate reversibly inactivates the nitrate reductase in *Chlorella vulgaris*, resembling cyanide inhibition. In *Setaria viridis* seedlings, Aihemaiti *et al*. (2019) also observed improved nutrient uptake at a low vanadium concentration; however, a contrasting effect occurs by toxicity at elevated levels. In peppers, García-Jiménez *et al*. (2018) reported enhanced shoot and flower development at a vanadium dose of 5–10 µM V and an inhibition at a higher vanadium dose (15 µM V). A broader review by Hanus-Fajerska *et al*. (2021) authenticated that vanadium activates the antioxidant systems and reduces stress conditions at low doses, while higher doses pose toxicity in terrestrial plants.

Based on the physiological role of vanadium on beet roots observed in this study, the significant increase in both root yield and sugar concentration aligns with previous findings. Vanadium has been noteworthy in stimulating both nitrate reductase activity and carbohydrate metabolism in higher plants, supporting improved nitrogen use and sucrose synthesis pathways. Additionally, numerous documentations of vanadium's role in enhancing antioxidant defenses and stress tolerance mechanisms have revealed its vital role as a growth regulator optimizing carbon partitioning toward sugar accumulation in plants (Aureliano *et al.,* 2023). This dual action—boosting enzymatic activity in normal conditions and exploring antioxidant defense in stress conditions—suggests vanadium with an appropriate dose could significantly improve sugar beet productivity and resilience. It is most particularly beneficial in regions like Eastern Europe facing increased climatic variability.

In this study, the vanadium treatments produced leading enhancements in sugar beet root yield and sugar concentration compared with typical effects of other microelements such as zinc and molybdenum. However, zinc's importance in photosynthesis and, particularly, its role in chlorophyll synthesis and photosynthetic enzyme activation is well documented (Alloway, 2008), and the effects observed with vanadium treatments extend beyond improved leaf function in this study. Notably, Singh and Wort's (1969) findings revealed that foliar application of vanadyl sulfate in sugar beet significantly increased sucrose-synthesizing enzyme activities (sucrose synthetase and sucrose phosphate synthetase), leading to measurable boosts in sucrose accumulation in beet roots under storage conditions. These considerable physiological changes represent a distinct and significant level of metabolic influence compared with zinc alone, especially relevant given the processing and storage quality considerations in industrial sugar beet production.

However, the limitations exist, with these results obtained under favorable growing conditions of the Western Forest-Steppe of Ukraine; thus, extrapolation to arid and highly saline soils should continue cautiously. Previous reports have also indicated that vanadium may interact negatively with excessive salinity and potentially decrease sugar yield (Kabata-Pendias and Mukherjee, 2007). Therefore, further multi-location investigations, including drought-prone regions, are necessary to validate the present results.

The promising research authenticated and filled a critical knowledge gap by demonstrating practical and field-level benefits of vanadium treatments in sugar beet production systems. Much of earlier research has focused on vanadium's physiological effects under controlled conditions, such as in *Chlorella vulgaris* (Ramadoss, 1979) and in mature sugar beet in foliar trials (Singh and Wort, 1969); however, these past studies missed the investigations through large-scale field trials for agronomic outcomes. This gap also contrasts with research on other biostimulants and microelements where both controlled and field studies succeeded, such as MagThio® and N-Sure® fertilizers being tested in field trials showing modest impacts on sugar beet root yield (Reitz *et al.,* 2020).

In this context, the presented findings on the positive agronomic effects of vanadium enhanced the root yield and sugar concentration. They suggested that vanadium-based microfertilizers, applied in carefully optimized doses, could bolster sugar beet yield and postharvest sugar recovery. However, responsible adoption would necessitate monitoring for soil accumulation and potential environmental risks. The integration of vanadium-based microfertilizers could therefore be a promising strategy to enhance both root yield and sugar recovery in commercial production of sugar beets, provided that application doses are optimal and long-term soil accumulation risks entail careful monitoring.

CONCLUSIONS

Field trials conducted between 2022 and 2024 showed foliar application of vanadium compounds increased the sugar beet (*B. vulgaris* L.) yield by 8%–12% and sucrose content by 1.1–2.1 percentage points. During the 90 days of storage, the weight loss and sucrose breakdown also declined. The most effective doses of vanadium (0.25–0.50 L ha^{-1}) proved to be optimal, while its excessive application reduced the yield and sugar purity. Thus, vanadium may be a promising tool in beet production under abiotic stress conditions, though further refinement of optimal dosing is essential.

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