Received: 19 December 2025 | Accepted: 16 April 2026

DOI: 10.1002/csc2.70303

Crop Science

ORIGINAL ARTICLE

Crop Ecology, Management & Quality

Genotype, mulching, and cropping system interactions drive vegetative growth and storage root yield in temperate-grown sweetpotato

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Assigned to Associate Editor Curtis Adams.

Funding information
The Slovenian Research and Innovation Agency; Javna Agencija za Raziskovalno Dejavnost RS (10.13039/501100004329), Grant/Award Number: P4-0072

Abstract

Understanding interactions among genotype, environment, and management is crucial for optimizing crop performance under climate variability. Sweetpotato (*Ipomoea batatas* (L.) Lam.), a nutrient-rich root crop increasingly cultivated in temperate regions, exhibits complex source-sink dynamics that remain insufficiently characterized in organic and mulch-based systems. This study evaluated vegetative growth and storage root yield of four varieties (Martina, Janja, Lučka, and Purple Speclet) grown under conventional and organic production, with and without polyethylene mulch, across two contrasting seasons (2021–2022) in Slovenia. A randomized complete block design with four replications was used to assess 15 agro-morphological traits, and linear mixed-effects models and multivariate analyses quantified factor effects and interactions. Variety and cultivation method predominantly influenced vegetative traits (η^2 = 30.26% and 24.85%), while variety and growing season contributed most to yield variance (35.56% and 20.88%). Polyethylene mulch significantly increased above-ground biomass (677–1329 g plant^{-1}) and total storage root yield (922–1548 g plant^{-1}), confirming its role in improving the soil-plant microenvironment. Martina showed the highest and most stable yield across systems. Pearson correlations indicated strong positive relationship among yield components (r = 0.77–0.93) and moderate positive correlations between vegetative biomass and yield (r = 0.49–0.60), reflecting coordinated yet distinct source-sink patterns. Principal component analysis separated treatment combinations and revealed significant genotype × management × season interactions, particularly under mulch in 2022. Overall, combining suitable varieties with polyethylene mulch substantially enhanced productivity, reducing the organic-conventional yield gap to ∼11%. These results support climate-adapted

Abbreviations: HFW, haulm fresh weight; LI, internode length; LPS, length of primary shoots; MLS, mature leaf size; NI, node number on the longest primary shoot; NL, number of leaves; NMRPP, number of marketable roots per plant; NRPP, number of storage roots per plant; PE, polyethylene mulch; PL, petiole length; PSN, primary shoot number; RD, root diameter; Rh, relative humidity; RL, root length; Rnfl, total rainfall; TWRPP, total root weight per plant; WMR, weight of marketable roots per plant.

strategies based on efficient resource use and optimized biomass partitioning in temperate agroecosystems.

Plain Language Summary

Sweetpotato (*Ipomoea batatas* (L.) Lam.) is a nutritious crop that can grow successfully in cooler regions, but farmers need guidance on best management practices. We tested four sweetpotato varieties in organic and conventional systems, with and without plastic mulch, over two very different growing seasons. Mulching nearly doubled plant size and increased yields by about 68%, demonstrating its strong effect on crop performance. The choice of variety and farming system was critically important, with one variety, Martina, performing consistently well across all conditions. Larger plants generally produced more roots, revealing a strong link between vegetative growth and yield. Our results show that combining the right variety with plastic mulch can help farmers grow sweetpotato more successfully and adapt to variable climates, supporting sustainable food production in temperate regions.

1 | INTRODUCTION

Sweetpotato (*Ipomoea batatas* (L.) Lam.) is a storage root crop of significant global importance, valued as a healthy and highly nutritious staple food. It is rich in carbohydrates, carotenoids, phenolic acids, minerals, fiber, vitamins, antioxidants, and anti-inflammatory compounds (Noreen et al., 2024) and provides the highgest amount of edible energy per hectare among major staple crops (Khoury et al., 2015). Its short production cycle, high yield potential, and adaptability to marginal growing conditions further distinguish it from other food crops (Truong et al., 2018). However, sweetpotato production in Europe remains very limited, accounting for <0.1% of global output, compared to 80.7% in Asia, 16.0% in Africa, and 2.6% in the Americas (Hossain et al., 2022). This disparity highlights both the untapped potential and the urgent need for research to support the expansion of this crop into temperate European farming systems.

In light of the serious consequences of climate change, a debate has emerged on the trade-off between food security and food safety, and thus between organic and conventional agriculture. While conventional systems generally achieve higher yields (Reganold & Wachter, 2016), they are increasingly scrutinized for their environmental footprint, including negative impacts on biodiversity, soil health, water quality, and greenhouse gas emissions (Schärer et al., 2022). This has catalyzed a growing global demand for organically grown storage roots (Barbieri et al., 2019). However, organic sweetpotato production is primarily constrained by weeds, which thrive in the absence of synthetic herbicides. Several previous studies have shown that mulching with plastic film is an effective approach to improve weed suppression (Nwosisi et al., 2021; Sideman, 2015) and significantly increases vegetative growth and storage root yield in sweetpotato (Shi et al., 2022; Wadl et al., 2023). In addition, yield component traits in sweetpotato are strongly influenced by environmental factors, resulting in significant genotype × season and genotype × management interactions (Ebem et al., 2021; Rukundo et al., 2020; Swanckaert et al., 2020). An important step in the development of promising genotypes/varieties is to assess the nature and extent of their interactions with the production environment by analyzing in detail the effects of the individual factors and their interactions (Lal et al., 2023). Such an assessment allows the performance of varieties with the dominant adaptation to be understood, which can perform consistently in different environments without compromising their yield potential (George et al., 2024).

Despite growing interest in sweetpotato cultivation in temperate regions, comprehensive studies that simultaneously examine the effects of variety selection, organic versus conventional management, and mulching practices across contrasting seasonal conditions are lacking. This study addresses these gaps by providing the first systematic field evaluation of three recently developed Slovenian varieties (Martina, Janja, and Lučka) alongside an international reference cultivar (Purple Speclet), all selected for their potential adaptation to temperate European conditions (Sinkovič et al., 2024). Their genotypic performance is assessed across all combinations of organic and conventional cropping systems, with and without polyethylene mulch (PE), generating the first integrated dataset on variety responses to these management practices in a temperate setting. Using a full factorial design, the study quantifies how interactions among growing season, cropping system, cultivation method, and variety jointly determine vegetative vigor and storage root yield, thereby identifying optimal variety-management combinations for temperate production. In addition to agronomic performance, it elucidates the source-sink dynamics linking above-ground biomass development to below-ground storage root formation, a physiological relationship previously documented only in tropical and subtropical contexts. Collectively, these contributions establish an empirical foundation for expanding sweetpotato cultivation into European farming systems and advance the fundamental understanding of crop adaptation to temperate agroecosystems.

Given the inherent complexity of these interacting factors, we hypothesized that (1) the cultivation method, particularly the use of PE, would significantly influence the balance between vegetative growth and storage root yield components; (2) varietal responses to management practices would show pronounced differences, with some genotypes demonstrating superior adaptation to specific systems; and (3) the trade-off between vegetative vigor and reproductive output would be modulated by both cropping system and cultivation method. The specific objectives were to quantify the individual and interactive effects of growing season, cultivation method, cropping system, and variety on vegetative growth and storage root yield parameters and to identify optimal variety-management combinations for sweetpotato production in temperate climates.

2 | MATERIALS AND METHODS

2.1 | Plant material and varieties

Four sweetpotato (*Ipomoea batatas* (L.) Lam.) varieties with contrasting morphological, agronomic, and nutritional characteristics were selected for this study. The three Slovenian varieties—Martina, Janja, and Lučka—were registered as protected varieties in the Slovenian National List of Varieties in 2016, following their development and evaluation under local conditions to support expanded production of this underutilized crop in Europe (Sinkovič et al., 2024; Žnidarčič et al., 2018). According to internationally recognized sweetpotato descriptor guidelines (IBPGR, 1991; UPOV, 2010) and detailed characterizations in comparative studies, Martina has purple skin and white (beige) flesh; Janja has white (light beige) skin and white (beige) flesh; and Lučka has brownish orange skin and orange (brownish orange) flesh (Sinkovič et al., 2024; Žnidarčič et al., 2018). These varieties differ notably in traits such as vine growth habit (all spreading), shoot and internode lengths (LIs), leaf morphology, storage root shape (predominantly ovate), yield components, and nutritional aspects, with Lučka often exhibiting higher total phenolic content and ascorbic acid in certain environments (Sinkovič et al., 2024; Žnidarčič et al., 2018). The fourth variety, Purple Speclet, is a commercially available American cultivar with purple skin and purple flesh, representing anthocyanin-rich sweetpotato types commonly grown in the United States (Sinkovič et al., 2024). This genotype consistently demonstrates superior nutritional traits, including higher dry matter, protein, vitamin C, total phenolic content, antioxidant potential, and total soluble solids, closely linked to its purple flesh and associated bioactive compounds, with strong genetic control over color and nutritional parameters across cropping systems, mulching treatments, and growing seasons (Sinkovič et al., 2024). Including Purple Speclet increased the genetic and phenotypic diversity of the experimental material, enabling comprehensive comparisons across flesh color groups (purple, white, and orange) and corresponding variations in agronomic performance and nutritional quality.

2.2 | Study site and environmental conditions

Field trials were conducted over two consecutive growing seasons (2021 and 2022) at the Biotechnical Centre Naklo, Slovenia (46°16′18″ N, 14°18′56″ E; 420 m a.s.l.). The soil at the experimental site is classified as an Umbric Planosol with a silty loam texture and a bulk density of 1.61 g cm^{-3}. The experiment was established within two long-term production systems that differed fundamentally in nutrient management and permitted inputs: conventional and organic. In the conventional system, basal fertilization consisted of NPK (15-15-15) at 400 kg ha^{-1} applied before planting, supplemented by calcium ammonium nitrate (27% N) at 150 kg N ha^{-1} at 30 days after planting (DAP). The organic system, certified in accordance with EU Regulation 2018/848, relied exclusively on composted cattle manure applied at 15 t ha^{-1} in the preceding autumn (average nutrient content: 0.8% N, 0.6% P_2O_5, 0.9% K_2O); no synthetic inputs were permitted. Weed control in both systems was manual, with the organic plots also using barley straw mulch to suppress weed emergence; no synthetic pesticides were applied in either system. Irrigation management was identical in both systems, with drip irrigation triggered when soil moisture dropped below 70% of field capacity, as determined by tensiometer readings at 20-cm depth. Within each production system, two cultivation methods were established: bare soil and black PE, applied across all four sweetpotato varieties, resulting in a full factorial arrangement of treatments (2 growing seasons × 2 cropping systems × 2 cultivation methods × 4 varieties). To fully characterize the growing environment for each system and year, comprehensive climatic and soil data were recorded. Climatic variables, including maximum, minimum, and mean air temperature (T_{max}, T_{min}, T_{med} [°C]), relative humidity (Rh; %), and total rainfall (Rnfl; mm), were obtained from a meteorological station adjacent to the experimental fields (Table 1).

Soil physicochemical properties were not experimentally controlled or homogenized across the conventional and organic plots; instead, they were considered an inherent component of the "production system environment," reflecting the

TABLE 1 Climatic conditions and baseline soil properties of the experimental site by year, cropping system, and cultivation method (2021–2022).

Year	Cultivation method	Cropping system	T_{max} (°C)	T_{min} (°C)	T_{med} (°C)	Rh (%)	Rnfl (mm)	pH	Available P (mg P_2O_5 100 g^{-1})	Available K (mg K_2O 100 g^{-1})	OM (%)	Nitrate-N (NO_3^--N) (mg kg^{-1})
2022	Bare soil	Conventional	17.3	5	10.8	76	966	7.2	25	37	5.9	5.3
2022	Bare soil	Organic	17.3	5	10.8	76	966	7.0	38	63	7.2	7.1
2021	Bare soil	Conventional	15.4	4	9.3	81	1267	6.8	20	41	5.4	5.9
2021	Bare soil	Organic	15.4	4	9.3	81	1267	6.8	22	50	5.3	6.8
2022	Polyethylene mulch	Conventional	17.3	5	10.8	76	966	7.2	25	37	5.9	5.3
2022	Polyethylene mulch	Organic	17.3	5	10.8	76	966	7.0	38	63	7.2	7.1
2021	Polyethylene mulch	Conventional	15.4	4	9.3	81	1267	6.8	20	41	5.4	5.9
2021	Polyethylene mulch	Organic	15.4	4	9.3	81	1267	6.8	22	50	5.3	6.8

Abbreviations: OM, soil organic matter; Rh, average relative humidity; Rnfl, total rainfall during the growing season (April–October); T_{max}, average daily maximum temperature; T_{med}, average daily mean temperature; T_{min}, average daily minimum temperature.

long-term effects of their contrasting management histories. To account for nutrient status and interannual variability, soil properties were monitored annually in the top 25 cm. At the start of each growing season (May, before planting and mulch application), representative composite soil samples were collected from the plough layer (0- to 25-cm depth) of each main plot. Samples were analyzed for pH in 1 M KCl, available phosphorus (P_2O_5) by the Olsen extraction method (Olsen et al., 1954) (mg 100 g^{-1} soil), available potassium (K_2O) by ammonium acetate extraction (Brown et al., 1999) (mg 100 g^{-1} soil), organic matter content by the Walkley–Black method (Walkley and Black, 1934) (%), and nitrate-nitrogen (NO_3^--N) in a 1 M KCl extract (Best, 1976) (mg kg^{-1} soil). Because soil samples were collected before cultivation methods were imposed, baseline fertility values were identical for plots designated for bare soil and PE within the same year and cropping system, as shown in Table 1.

2.3 | Experimental design

The experiment was arranged as a 2 × 2 × 2 × 4 full factorial design (2 growing seasons × 2 cropping systems [conventional, organic] × 2 cultivation methods [bare soil, PE] × 4 varieties [Martina, Janja, Lučka, and Purple Speclet]) within a randomized complete block design with four replications per variety in each cropping system and year. This factorial structure enabled the estimation and testing of all main effects and interactions, including the four-way interaction (Y × CS × CM × V, where Y, CS, CM, and V are year, cropping system, cultivation method, and variety). Each replicate consisted of 15 plants. The planting material comprised 20-cm-long vegetative cuttings propagated in the greenhouse. The cuttings were obtained from healthy storage roots harvested during the previous growing season and contained at least five nodes. Cuttings were transplanted at the beginning of June in both years on ploughed and harrowed soil ridges at a spacing of 120 cm between rows and 40 cm within rows. Two cultivation treatments were applied: bare soil and PE. Barley straw mulch was applied uniformly between rows in all plots as a standard weed management practice; it was not an experimental treatment factor in the study design.

2.4 | Data collection and measurements

At harvest, fifteen agro-morphological traits related to vegetative growth (nine traits: primary shoot number [PSN], number of internodes [NI], length of primary shoots [LPS], LI, internode diameter [DI], petiole length [PL], mature leaf size [MLS], number of leaves [NL], and haulm fresh weight [HFW]) and storage root yield (six traits: number of storage roots per plant [NRPP], total root weight per plant [TWRPP], number of marketable roots per plant [NMRPP], weight of marketable roots per plant [WMR], storage root diameter [RD], storage root length [RL]) were evaluated according to standardized sweetpotato descriptor guidelines (IBPGR, 1991; UPOV, 2010). A complete list of traits with their abbreviations, units, and descriptions is provided in Table 2.

2.5 | Statistical analysis

All statistical analyses were conducted using R version 4.3.2 (R Core Team, 2023). To account for the hierarchical structure of the experiment, with growing seasons (years) as fixed envi-

TABLE 2 List of agro-morphological traits evaluated in sweetpotato with their abbreviations, units, and descriptions.

Trait category	Abbreviation	Trait name	Unit	Description
Vegetative	PSN	Primary shoot number	count	Number of primary shoots per plant
Vegetative	NI	Number of internodes	count	Number of internodes on the longest primary shoot
Vegetative	LPS	Length of primary shoots	cm	Length of the longest primary shoot
Vegetative	LI	Internode length	cm	Average internode length on the longest primary shoot
Vegetative	DI	Internode diameter	mm	Diameter of the longest primary shoot at mid-length
Vegetative	PL	Petiole length	cm	Length of the petiole from the largest mature leaf
Vegetative	MLS	Mature leaf size	cm	Length of the largest mature leaf blade
Vegetative	NL	Number of leaves	count	Total number of leaves on the longest primary shoot
Vegetative	HFW	Haulm fresh weight	g plant^{-1}	Fresh weight of above-ground vegetative biomass
Yield	NRPP	Number of storage roots	count plant^{-1}	Total number of storage roots per plant
Yield	TWRPP	Total root weight per plant	g plant^{-1}	Total fresh weight of all storage roots per plant
Yield	NMRPP	Number of marketable roots per plant	count plant^{-1}	Number of storage roots ≥150 g per plant
Yield	WMR	Weight of marketable roots per plant	g plant^{-1}	Total fresh weight of marketable storage roots per plant
Yield	RD	Storage root diameter	cm	Maximum diameter of the largest storage root
Yield	RL	Storage root length	cm	Maximum length of the largest storage root

ronments and blocks nested within them, linear mixed-effects (LME) models were fitted using the *nlme* package (Pinheiro et al., 2025). The model included the fixed effects of growing season (year), cultivation method (bare soil vs. PE), cropping system (conventional vs. organic), and variety (Martina, Janja, Lučka, and Purple Speclet), along with all two-way, three-way, and four-way interactions to assess potential cross-scale treatment effects. The random component was specified as a random intercept for each unique block-within-year combination (Year:Block), directly reflecting the physical layout of the randomized complete block design in each environment. This structure prevents pseudoreplication by accounting for the spatial correlation of plots within the same block and year (Piepho et al., 2003). Individual plants (n = 15 per plot) constituted the observational unit; pseudoreplication is prevented by the random intercept term (Year:Block), which correctly partitions variance between the plot/block level and the residual plant-level variation, ensuring that the effective degrees of freedom for fixed effects reflect the number of plots, not individual plants. The full model is represented as follows:

$$\begin{aligned} \text{R\_ijklm} &= \mu + \text{Y\_i} + \text{CM\_j} + \text{CS\_k} + \text{V\_l} + (\text{Y}:\text{CM})\text{\_ij} \\ &+ (\text{Y}:\text{CS})\text{\_ik} + (\text{Y}:\text{V})\text{\_il} + (\text{CM}:\text{CS})\text{\_jk} \\ &+ (\text{CM}:\text{V})\text{\_jl} + (\text{CS}:\text{V})\text{\_kl} + (\text{Y}:\text{CM}:\text{CS})\text{\_ijk} \\ &+ (\text{Y}:\text{CM}:\text{V})\text{\_ijl} + (\text{Y}:\text{CS}:\text{V})\text{\_ikl} \\ &+ (\text{CM}:\text{CS}:\text{V})\text{\_jkl} + (\text{Y}:\text{CM}:\text{CS}:\text{V})\text{\_ijkl} \\ &+ \text{b\_\{m(i)\}} + \varepsilon\text{\_ijklm}, \end{aligned}$$

where R_ijklm is the observed response; μ is the overall mean; Y_i, CM_j, CS_k, and V_l are the main fixed effects; terms in parentheses represent interactions; b_{m(i)} is the random intercept for Block m nested within Year i, with b ~ N(0, σ^2_Block); and ε_ijklm is the residual error, with $\varepsilon \sim N(0, \sigma^2)$. Models were fitted in nlme using the syntax: lme(Response ~ Year * Method * System * Variety, random = ~1 | Year:Block, data = dataset).

The proportion of variance explained by each factor (η^2) was calculated as the ratio of a factor's sum of squares to the total sum of squares from the analysis of variance (ANOVA) model. Prior to hypothesis testing, model assumptions of normality and homoscedasticity of residuals were verified by visually inspecting *Q*–*Q* plots and residual plots. For fixed effects identified as significant (p < 0.05), post hoc pairwise comparisons were conducted using Tukey's honestly significant difference test via the *glht* function from the *multcomp* package (Hothorn, 2025), ensuring strong control of the family wise error rate. To address the risk of Type I error inflation from multiple testing across the 15 dependent variables, we applied a false discovery rate (FDR) correction using the Benjamini–Hochberg procedure (Benjamini & Hochberg, 1995) to all p-values from the ANOVA F-tests. Effects were considered robust if they remained significant at an FDR-adjusted q < 0.05.

To explore relationships among agro-morphological traits, Pearson correlation coefficients were computed and visualized using the *corrplot* package (Wei et al., 2017). To understand the multivariate response of varieties to different treatment combinations, principal component analysis (PCA)

TABLE 3 Least squares means (± standard error) and Tukey's honestly significant difference (HSD) grouping for growth parameters of sweetpotato as affected by cultivation method, variety, cropping system, and year.

Factor	*n*	LPS (cm)	PSN	NI	LI (cm)	PL (cm)	MLS (cm)	DI (mm)	NL	HFW (g plant^{-1})
Cultivation method										
PE	960	127.7 ± 1.15a	1.08 ± 0.01a	31.86 ± 0.72a	3.71 ± 0.03a	12.39 ± 0.10a	10.86 ± 0.06a	14.50 ± 0.17a	333.05 ± 5.02a	1329.38 ± 23.60a
Soil	960	92.23 ± 1.03b	1.03 ± 0.01b	25.02 ± 0.74b	3.54 ± 0.02b	11.59 ± 0.09b	10.94 ± 0.07a	10.76 ± 0.11b	200.47 ± 3.15b	677.14 ± 14.83b
Variety										
Janja	480	103.35 ± 1.65b	1.05 ± 0.01a	31.30 ± 1.03a	3.31 ± 0.03c	11.33 ± 0.13c	10.12 ± 0.07c	13.14 ± 0.24b	307.56 ± 7.17a	1115.95 ± 36.29a
Lučka	480	105.40 ± 1.61b	1.06 ± 0.01a	27.29 ± 1.00b	3.77 ± 0.03b	10.38 ± 0.12d	9.80 ± 0.09b	12.28 ± 0.20c	209.89 ± 5.45c	745.65 ± 24.35b
Martina	480	113.42 ± 1.64a	1.05 ± 0.01a	30.96 ± 1.36a	3.35 ± 0.03c	12.78 ± 0.15b	11.56 ± 0.08d	14.07 ± 0.21a	278.04 ± 6.12b	1102.87 ± 29.61a
Purple Speclet	480	117.69 ± 1.98a	1.07 ± 0.01a	24.21 ± 0.59b	4.05 ± 0.03a	13.46 ± 0.12a	12.13 ± 0.08a	11.05 ± 0.21d	271.53 ± 6.94b	1048.58 ± 31.96a
Cropping system										
CONV	960	114.27 ± 1.19 a	1.05 ± 0.01b	31.65 ± 0.87a	3.59 ± 0.02a	12.13 ± 0.10a	10.84 ± 0.06a	12.85 ± 0.16a	264.32 ± 4.62a	969.21 ± 20.07b
ECO	960	105.67 ± 1.26b	1.07 ± 0.01a	25.23 ± 0.55b	3.66 ± 0.02a	11.84 ± 0.10b	10.97 ± 0.07a	12.42 ± 0.15a	269.20 ± 4.79a	1037.32 ± 24.36a
Year										
2021	960	96.65 ± 1.03b	1.06 ± 0.01a	27.64 ± 0.90a	3.59 ± 0.02a	11.67 ± 0.09b	10.88 ± 0.06a	11.37 ± 0.12b	271.17 ± 4.18a	811.49 ± 16.31b
2022	960	123.28 ± 1.27a	1.06 ± 0.01a	29.24 ± 0.52a	3.65 ± 0.03a	12.30 ± 0.11a	10.92 ± 0.07a	13.90 ± 0.18a	262.34 ± 5.17a	1195.04 ± 25.61a

Note: Values are least squares means (LS means) derived from the mixed model adjusted for all other factors in the analysis. Within each factor and column, means followed by different lowercase letters are significantly different (Tukey's HSD, $p < 0.05$). Sample size (*n*) represents the total number of individual plants per factor level across both years.

Abbreviations: CONV, conventional; DI, diameter of the longest primary shoot (mm); ECO, organic; HFW, haulm fresh weight (g plant^{-1}); LI, internode length (cm); LPS, length of primary shoots (cm); MLS, maturee leaf size (cm); NI, number of internodes; NL, number of leaves on the longest primary shoot; PE, polyethylene mulch; PL, petiole length (cm); PSN, primary shoot number.

was conducted using *FactoMineR* (Lê et al., 2008). Results were visualized with *factoextra* (Kassambara & Mundt, 2017) to illustrate phenotypic differentiation among the four sweetpotato varieties under the combined influence of cultivation method, cropping system, and growing season.

3 | RESULTS

3.1 | Vegetative growth performance

ANOVA based on LME models showed that all nine vegetative growth parameters (primary shoot number, number of internodes, LPS, LI, internode diameter, PL, mature leaf size, number of leaves, and HFW) were significantly affected by the main factors, except for the non-significant effects of year on primary shoot number and mature leaf size, cropping system on number of leaves, and cultivation method on mature leaf size (Table S1; Table 3). Variety and cultivation method accounted for the largest proportions of explained variance (η^2) for the vegetative traits, averaging 30.26% and 24.85%, respectively, indicating their predominant influence on above-ground biomass development (Table S1).

3.1.1 | Variety response

Significant differences among varieties were observed for all measured vegetative traits except primary shoot number (Table 3; Table S1). Variety effects were especially pronounced for LI, mature leaf size, and PL, explaining 82.54%, 68.35%, and 66.89% of the variance, respectively (Table S1), indicating strong genetic control over these morphological traits. Among the varieties, Purple Speclet displayed distinct morphological characteristics, with the longest internodes (4.05 cm), longest petioles (13.46 cm), and largest mature leaf size (12.13 cm) (Table 3). Martina and Purple Speclet produced the longest primary shoots (113.42 and 117.69 cm, respectively), significantly exceeding Janja (103.35 cm) and Lučka (105.40 cm). Notably, Janja developed the most leaves per plant (307.56) and the highest HFW (1115.95 g plant^{-1}), while Lučka consistently exhibited lower values for most vegetative parameters and the lowest HFW (745.65 g plant^{-1}).

3.1.2 | Cultivation method effects

Cultivation method significantly affected all measured vegetative traits except mature leaf size, with the strongest effects on number of leaves (52.86% of variance explained), HFW (48.96%), and LPS (39.42%) (Table S1). PE substantially enhanced vegetative growth compared to bare soil. Plants grown on PE developed greater primary shoot length (127.7 vs. 92.23 cm), primary shoot number (1.08 vs. 1.03), number of internodes (31.86 vs. 25.02), LI (3.71 vs. 3.54 cm), and PL (12.39 vs. 11.59 cm) (Table 3). The most notable difference was in HFW, where PEed plants produced nearly double the haulm biomass (1329.38 g plant^{-1}) compared to those on bare soil (677.14 g plant^{-1}).

3.1.3 | Year effects

The effect of growing season on vegetative growth was modest compared to variety and cultivation method, with an average explained variance of 7.05% across all traits (Table S1). Significant year effects were observed for LPS (22.22% variance explained), internode diameter (18.1%), and HFW (16.93%) (Table S1). The 2022 growing season resulted in substantially stronger vegetative growth than 2021, with increases in primary shoot length (123.28 vs. 96.65 cm) and HFW (1195.04 vs. 811.49 g plant^{-1}) (Table 3). These differences can be attributed to contrasting climatic conditions between the two seasons, including higher temperatures, lower rainfall, and reduced RH in 2022 compared to 2021 (Table 1).

3.1.4 | Cropping system effects

Although significant for certain traits, cropping system effects explained a smaller proportion of variance (average 2.08%) than cultivation method, year, or variety (Table S1). The largest cropping system effect was observed for number of internodes (8.12% variance explained), with number of internodes increasing from 25.23 ± 0.55 under organic management to 31.65 ± 0.87 under conventional systems (Table 3). The conventional cropping system also promoted significantly longer primary shoots (114.27 cm) compared to organic management (105.67 cm). In contrast, organic management resulted in higher haulm biomass (1037.32 g plant^{-1}) than conventional systems (969.21 g plant^{-1}), suggesting different resource allocation patterns between the two systems.

3.1.5 | Interaction effects

Following the principle of hierarchical interpretation, higher-order interactions were examined before lower-order and main effects (Table 3; Table S1). The four-way interaction among year, cropping system, cultivation method, and variety (Y × CS × CM × V) was significant for LPS, number of internodes, mature leaf size, and number of leaves (Table S1). To visualize these complex interactions, least squares means for each trait are presented in Figure 1, with panels arranged by year and cropping system, and bars grouped by cultivation method for each variety. The plots revealed that the magnitude of the mulching effect varied considerably among varieties and depended on both the cropping system and the growing season. For example, in 2022 under the conventional system, PE increased primary shoot length in Martina by approximately 40 cm, whereas under organic management, the increase was less pronounced. Similarly, number of internodes responded more strongly to mulch in 2022 than in 2021, especially in Purple Speclet and Lučka. These visualizations highlight the genotype-specific and environment-dependent benefits of mulching, supporting the need for integrated management strategies. The three-way interaction among Y × CS × CM was statistically significant for most vegetative traits after FDR correction. However, it explained on average only 2.38% of the total variance across traits, indicating that its practical agronomic importance is modest compared to the dominant main effects (Table S1). This interaction was most pronounced for LPS, where Y × CS × CM accounted for 7.73% of the total variance (Table S1). Among two-way interactions, Y × CS was the dominant source of interaction variance, reaching high significance for most parameters ($p < 0.001$) and explaining an average of 12.34% of the variance across traits. The effect was especially large for number of internodes (44.36%), number of leaves per plant (20.07%), HFW (15.30%), and mature leaf size (10.73%) (Table S1). The Y × CM interaction was also significant, though smaller in magnitude (average 4.01% of the variance across traits) (Table S2), with the largest contribution observed for LPS (10.87%) (Table S1). The V × CM interaction explained an average of 3.23% of the variance across traits (Table S1). While all varieties exhibited improved performance under PE, the magnitude of response differed among genotypes. The most notable improvements were observed in Janja, where mean HFW increased from 671 g to 1561 g under mulch, and

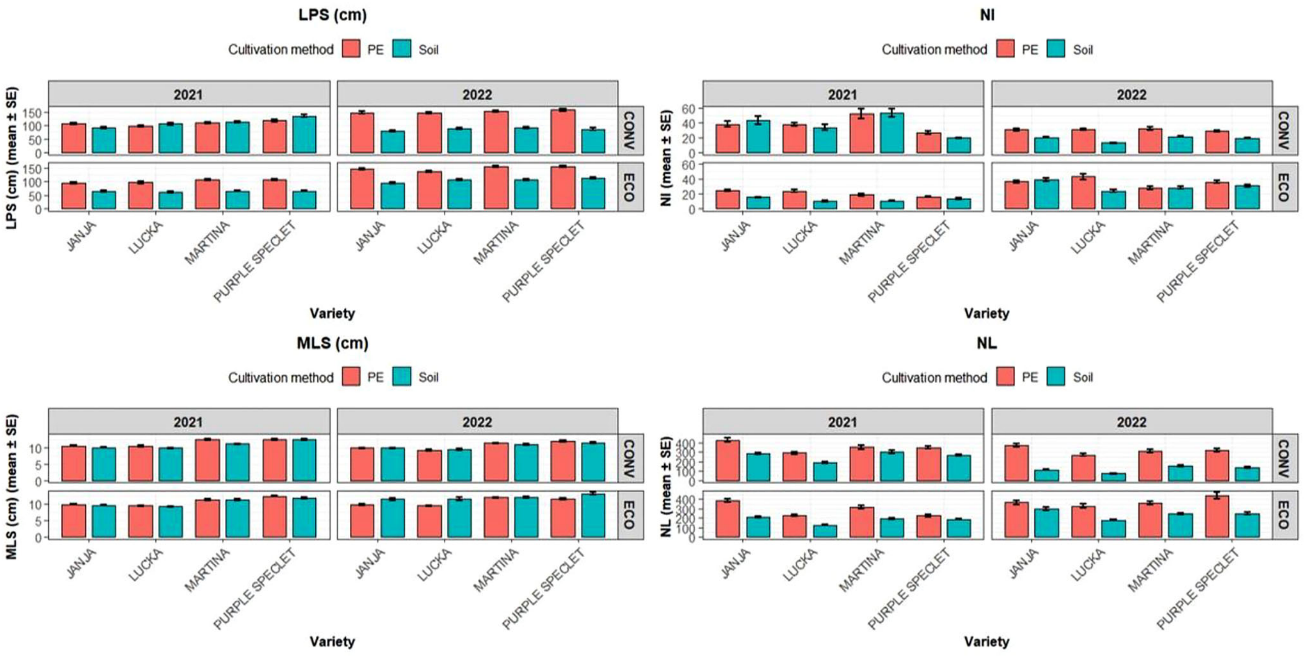

FIGURE 1 Four-way interaction (year × cropping system × cultivation method × variety) for vegetative traits (length of primary shoots [LPS], number of internodes [NI], mature leaf size [MLS], and number of leaves per plant [NL]). Bars represent least squares means and error bars indicate standard errors. PE, polyethylene mulch; Soil, bare soil.

in Purple Speclet, where mean LPS increased from 100.3 to 135.1 cm (Table S3).

3.2 | Yield and storage root characteristics

The ANOVA revealed that all six yield-related traits (NRPP, TWRPP, number of marketable storage roots per plant, weight of marketable storage roots, storage RD, and storage RL) were significantly influenced by all main factors, with the exception of the non-significant effect of cropping system on RD (Table 4). The largest proportion of variance across traits was explained by variety and growing season, averaging 35.56% and 20.88%, respectively.

3.2.1 | Variety response

Significant differences between the varieties were found for all yield-related traits (Table 4; Table S2). Variety effects were particularly pronounced for storage root morphology, explaining 51.87% and 40.56% of the variance in RD and RL, respectively (Table S2). Number of marketable storage roots per plant and TWRPP were also strongly influenced by variety, accounting for 35.65% and 32.93% of the explained variance, respectively. Variety had the least influence on NRPP with an explained variance of 23.28% (Table S2). Martina showed superior performance for all yield parameters and produced a significantly higher NRPP (13.15), TWRPP (1800.55 g), and number of marketable storage roots per plant (3.78) compared to the other varieties (Table 4). Lučka ranked second in yield performance with remarkable storage root dimensions (RD: 5.57 cm; RL: 16.57 cm), but produced fewer storage roots per plant (10.28). Purple Speclet did not differ significantly from Lučka in NRPP (9.99) but had lower values for all other yield parameters. In contrast, Janja had consistently lower values for all yield parameters and produced 34% fewer storage roots per plant (13.15 vs. 9.73) and less than half the total storage root weight (1800.55 vs. 830.02 g) compared to Martina.

3.2.2 | Year effects

The effects of growing season on yield parameters were highly significant ($p < 0.0001$) and explained 25.69% of the variance in RL, 25.42% in number of marketable storage roots, 23.2% in total storage root weight, and 21.55% of the variance in RD (Table S2). Contrasting patterns were observed in the two growing seasons. While 2021 favored storage root number formation (NRPP; 11.65 vs. 9.93), 2022 significantly improved storage root weight parameters, with total storage root weight increasing by 57% (1509.05 vs. 960.79 g) and marketable storage root weight by 113% (1120.8 vs. 525.86 g) (Table 4).

TABLE 4 Least squares means (± standard error) and Tukey's honestly significant difference (HSD) grouping for yield and yield-related traits of sweetpotato as affected by cultivation method, variety, cropping system, and year.

Factor	*n*	NRPP	TWRPP (g plant^{-1})	NMRPP	WMR (g plant^{-1})	RD (mm)	RL (cm)
Cultivation method							
PE	960	11.39 ± 0.20a	1547.67 ± 33.45a	3.05 ± 0.07a	1132.48 ± 32.19a	5.12 ± 0.08a	14.34 ± 0.21a
Soil	960	10.19 ± 0.26b	922.17 ± 16.65b	1.92 ± 0.05b	514.18 ± 15.15b	4.25 ± 0.08b	13.53 ± 0.24b
Variety							
Janja	480	9.73 ± 0.29b	830.02 ± 32.01d	1.56 ± 0.09d	436.78 ± 29.25d	3.18 ± 0.12c	10.29 ± 0.40c
Lučka	480	10.28 ± 0.27b	1355.86 ± 36.53b	2.66 ± 0.07b	1010.32 ± 36.03b	5.57 ± 0.08a	16.57 ± 0.26a
Martina	480	13.15 ± 0.45a	1800.55 ± 48.27a	3.78 ± 0.11a	1286.44 ± 47.65a	5.69 ± 0.09a	16.24 ± 0.23a
Purple Speclet	480	9.99 ± 0.23b	953.25 ± 22.63c	1.95 ± 0.07 c	559.78 ± 21.52c	4.29 ± 0.1b	12.65 ± 0.29b
Cropping system							
CONV	960	11.28 ± 0.2a	1306.27 ± 30.08a	2.6 ± 0.07a	872.28 ± 29.18a	4.69 ± 0.08a	14.95 ± 0.24a
ECO	960	10.29 ± 0.26b	1163.58 ± 26.17b	2.38 ± 0.06b	774.38 ± 24.66b	4.68 ± 0.08a	12.92 ± 0.22b
Year							
2021	960	11.65 ± 0.26a	960.79 ± 19.71b	1.8 ± 0.05b	525.86 ± 16.81b	4.03 ± 0.08b	11.92 ± 0.23b
2022	960	9.93 ± 0.19b	1509.05 ± 32.48a	3.17 ± 0.07a	1120.8 ± 31.59a	5.33 ± 0.07a	15.95 ± 0.20a

Note: Values are least squares means (LS means) derived from the mixed model, adjusted for all other factors in the analysis. Within each factor and column, means followed by different lowercase letters are significantly different (Tukey's HSD, $p < 0.05$). Sample size (*n*) represents the total number of individual plants per factor level across both years.

Abbreviations: CONV, conventional; ECO, organic; NMRPP, number of marketable roots per plant; NRPP, number of storage roots per plant; PE, polyethylene mulch; RD, root diameter (mm); RL, root length (cm); TWRPP, total root weight per plant (g); WMR, weight of marketable roots per plant (g).

3.2.3 | Cultivation method effects

The cultivation method significantly influenced all yield components ($p < 0.0001$) (Table 4; Table S2). PE significantly improved all yield parameters compared to cultivation on bare soil, with the strongest effects on total storage root weight (24.37%) and marketable weight (25.05%), with an average explained variance of 13.72% across all traits (Table S2). Plants grown with PE produced higher total storage root weight (1547.67 vs. 922.17 g) and number of marketable storage roots (3.05 vs. 1.92) compared to those grown on bare soil.

3.2.4 | Cropping system effect

The cropping system, although significant, showed relatively small effects on yield parameters, with the largest effect on RL (6.53%, $p < 0.0001$) and an average explained variance across all traits of 2.1% (Table S2). The conventional cropping system generally performed better than organic, producing higher total storage root weight (1306.27 vs. 1163.58 g) and number of marketable storage roots (2.60 vs. 2.38). In particular, the RL showed no significant difference between the cropping systems.

3.2.5 | Interaction effects

Significant four-way interactions were detected for the key yield components NRPP, total storage root weight, number of marketable storage roots, and marketable weight (Table S2; Figure 2). In both cropping systems, PE consistently increased total storage root weight and marketable weight across all varieties, but the magnitude of the increase was strongly influenced by year and variety. Martina achieved the highest total storage root weight under PE in 2022, reaching 3146.866 g plant^{-1} in the conventional system, while Janja and Purple Speclet showed more moderate gains (Table S3). The number of marketable roots followed a similar pattern, with Martina producing the most marketable roots under mulch in 2022. Overall, the interaction plots demonstrated that Martina's superior yield under PE is not simply a main effect but results from a synergistic combination of genetic potential, favorable seasonal conditions, and the modified microclimate created by the mulch. The three-way interaction among Y × CS × CM had significant effects ($p < 0.0001$) on most yield parameters, with the strongest effects on RL (8.59%) and marketable storage root traits (≥3.58%) (Table S2). Among the two-way interactions, Y × CM had the largest effect on yield performance, showing highly significant effects on all parameters except RD. It explained 14.44% of the variance in number of storage roots, 10.54% in total storage root weight, and averaged 7.15% across all traits (Table S2). This indicates that the response of storage root yield to mulching practices is strongly influenced by seasonal conditions. The interaction Y × CS was particularly important for number of storage roots (19.46%), indicating that the efficiency of the cropping system is highly dependent on seasonal conditions (Table S2). This was especially evident for storage root initiation, where the conventional system had a greater advantage in 2021 than

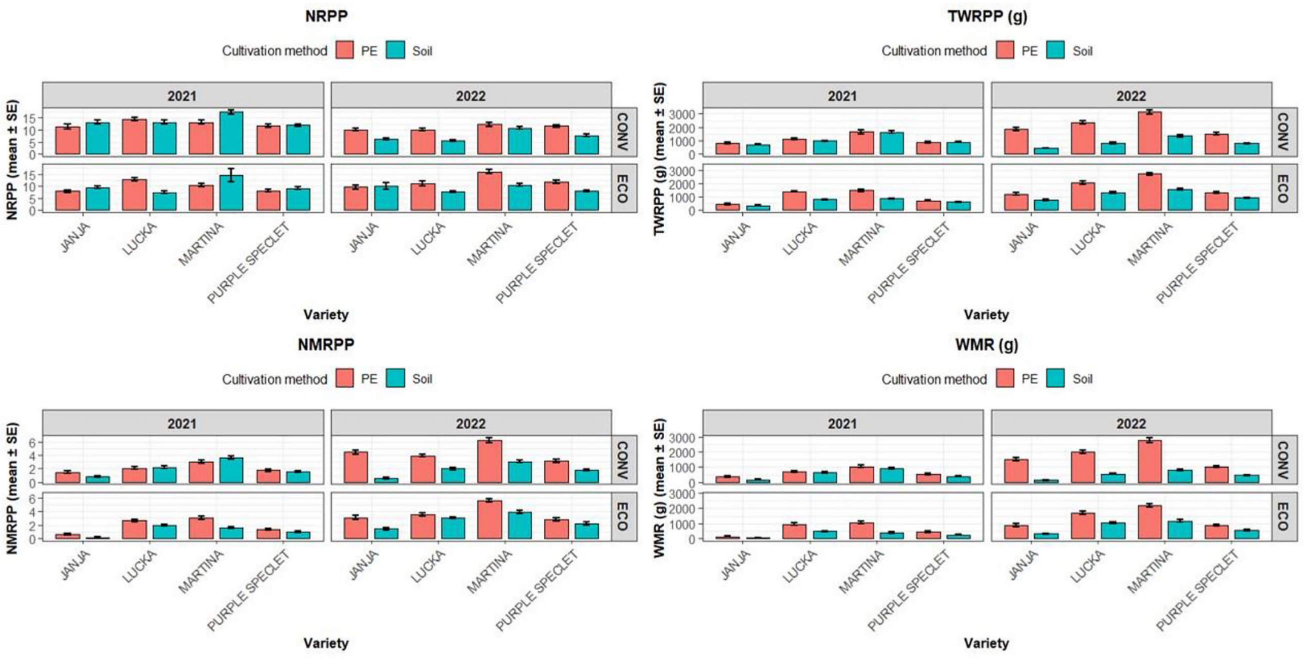

FIGURE 2 Four-way interaction (year × cropping system × cultivation method × variety) for yield traits (number of storage roots per plant [NRPP], total root weight per plant [TWRPP], number of marketable roots per plant [NMRPP], and weight of marketable roots per plant [WMR]). Bars represent least squares means (from Table S3) and error bars indicate standard errors. PE, polyethylene mulch; Soil, bare soil.

in 2022. The V × CM interaction explained 8.00%, 2.85%, and 2.03% of the variance in number of storage roots, total storage root weight, and number of marketable storage roots, respectively (Table S2). Overall, while the three-way interaction is statistically significant for most yield traits, its contribution to total variance is modest compared to key two-way interactions (particularly Y × CM and Y × CS) and main effects. This suggests that practical management recommendations for optimizing storage root yield can be based on these more influential effects, with particular attention to the strong seasonal influence on mulching benefits and cropping system performance.

In addition to the four-way interactions, several traits exhibited significant three-way interactions (Tables S1 and S2). To facilitate interpretation of these conditional effects, Figure S1 presents least squares means for all significant three-way combinations involving the traits primary shoot number, PL, internode diameter, RD, and RL. The panels are arranged by trait and specific interaction term. For example, primary shoot number is shown for the CS × CM × V interaction, revealing that the effect of mulching on primary shoot number depended on both the cropping system and the variety. Internode diameter, RD, and RL each had multiple significant three-way interactions; the figure includes panels for Y × CS × CM, Y × CS × V, Y × CM × V, and CS × CM × V, allowing direct visual comparison of how seasonal conditions, management practices, and genetic background jointly influence these root traits. These plots underscore the complexity of the responses and highlight that optimal management strategies must consider the interplay of all three factors.

3.3 | Correlation among growth and yield parameters and multivariate analysis

The correlation analyses revealed distinct patterns among vegetative growth and yield-related traits, as shown in the hierarchically clustered Pearson correlation matrix (Figure 3). The clustering clearly delineated two primary groups: a tightly interconnected yield component group (number of marketable storage roots, total storage root weight, marketable weight, RD, RL, and number of storage roots) characterized by strong positive inter-correlations, and a more loosely associated vegetative growth group (internode diameter, LPS, HFW, number of internodes, number of leaves, LI, PL, mature leaf size, and primary shoot number) with moderate internal links and some cross-group connections. Within the yield-related traits, TWRPP showed very strong positive correlations with weight of marketable storage roots ($r = 0.93$, $p < 0.001$) and number of marketable storage roots ($r = 0.86$, $p < 0.001$), underscoring a highly synchronized developmental pathway for marketable yield. Marketable weight and number of marketable storage roots were also strongly associated ($r = 0.83$, $p < 0.001$). Storage root morphological traits, such as diameter and length, had robust positive correlations with total storage root weight ($r = 0.77$ for both; $p < 0.001$), emphasizing their pivotal role in determining overall storage root

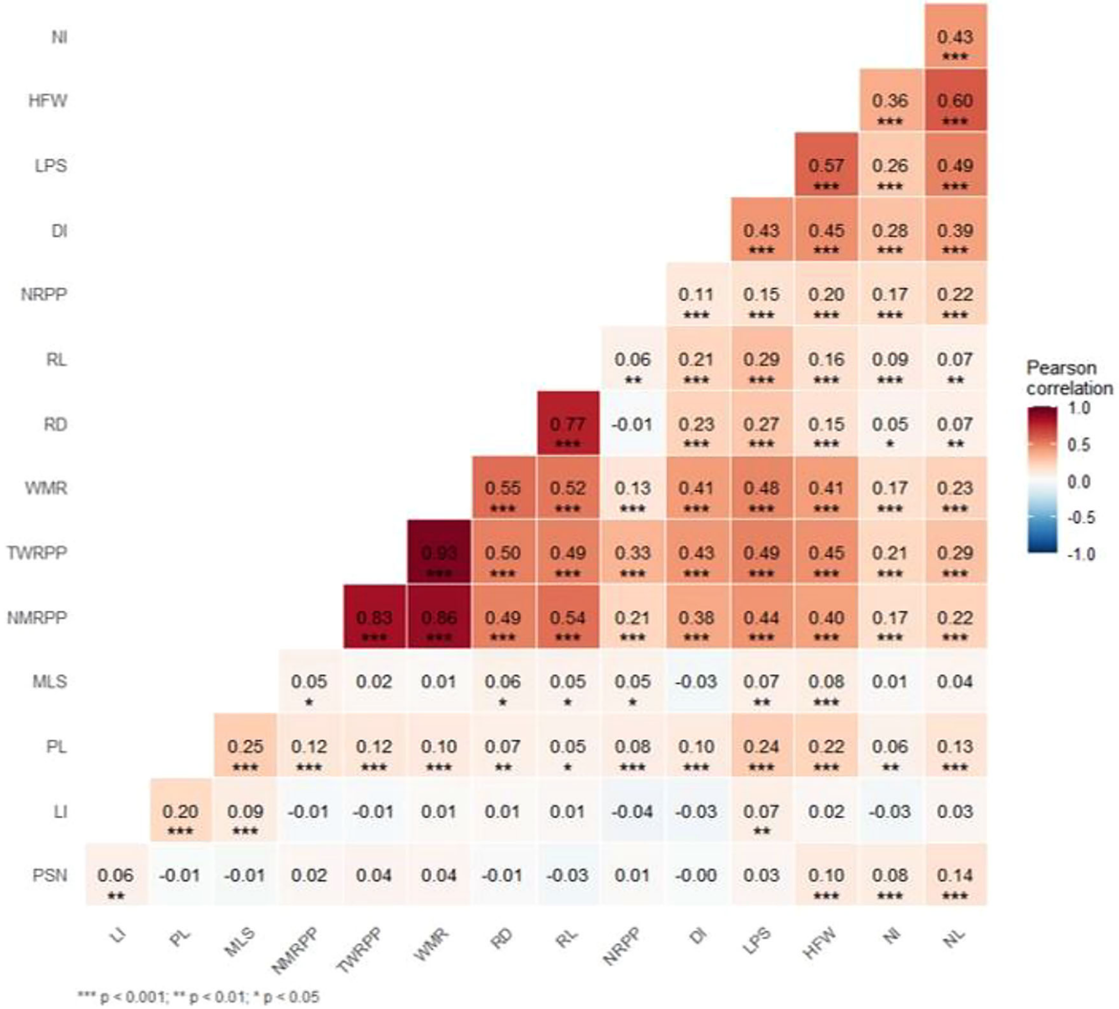

FIGURE 3 Pearson correlation coefficients (r) among 15 traits in the studied sweetpotato varieties. Significance levels are indicated as *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. Traits are reordered using hierarchical clustering to highlight groups of related variables. Trait LPS, length of primary shoots (cm); PSN, primary shoot number; NI, number of internodes; LI, internode length (cm); DI, internode diameter (mm); PL, petiole length (cm); MLS, mature leaf size (cm); NL, number of leaves per plant; HFW, haulm fresh weight (g plant^{-1}); NRPP, number of storage roots per plant; TWRPP, total root weight per plant (g); NMRPP, number of marketable roots per plant (≥150 g) per plant; WMR, weight of marketable roots per plant (g); RD, storage root diameter (cm); RL, storage root length (cm).

productivity and marketability. Vegetative traits demonstrated coordinated interrelationships, with HFW strongly correlated with internode diameter ($r = 0.83$, $p < 0.001$) and number of leaves ($r = 0.60$, $p < 0.001$) and moderately with LPS ($r = 0.57$, $p < 0.001$). LPS was a central node in vegetative coordination, showing moderate to strong positive correlations with PL ($r = 0.72$, $p < 0.001$), number of leaves ($r = 0.71$, $p < 0.001$), and internode diameter ($r = 0.64$, $p < 0.001$), indicating integrated shoot architecture development. Several vegetative traits bridged to yield components, revealing consistent associations between above-ground vigor and below-ground productivity. HFW displayed moderate positive associations with total storage root weight ($r = 0.60$, $p < 0.001$), marketable weight ($r = 0.54$, $p < 0.001$), and number of marketable storage roots ($r = 0.49$, $p < 0.001$), while LPS correlated moderately with total storage root weight ($r = 0.57$, $p < 0.001$) and marketable weight ($r = 0.49$, $p < 0.001$), suggesting that enhanced vegetative biomass allocation supports storage root yield optimization. However, traits such as LI and primary shoot number showed negligible or non-significant correlations with yield parameters (all $|r| < 0.20$, $p > 0.05$), indicating that these vegetative traits do not serve as reliable predictors of storage root yield under the conditions of this study.

To elucidate multivariate patterns among sweetpotato varieties and treatment combinations across growing environments, PCA was conducted on 15 agro-morphological traits. The first two principal components, with eigenvalues of 6.90 and 2.33, together explained 61.53% of the total variance (PC1: 46.00%; PC2: 15.53%; Figure 4; Table S4). PC1 was strongly associated with productivity-related traits, as indicated by the highest positive loadings for number of mar-

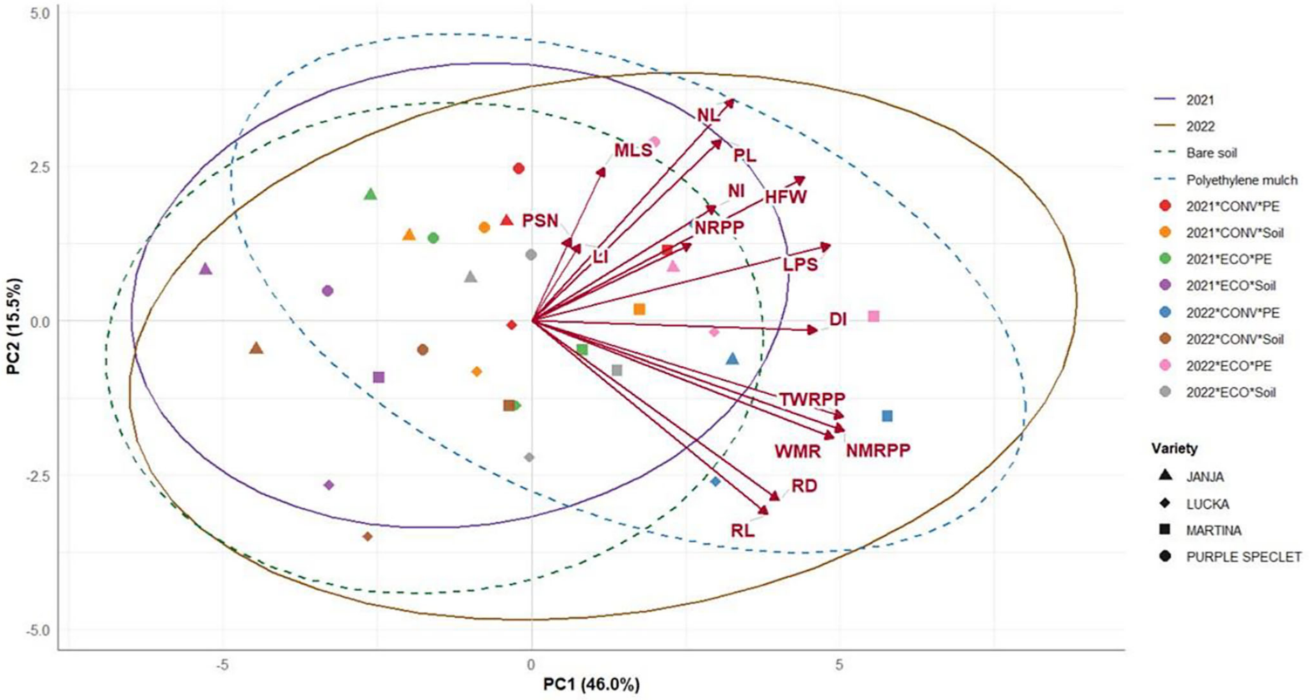

FIGURE 4 Principal component analysis (PCA) biplot of agro-morphological traits in sweetpotato varieties. Points are colored by management combination and shaped by variety. Solid ellipses indicate 95% confidence regions by year; dashed ellipses indicate 95% confidence regions by mulch type. CONV, conventional; DI, internode diameter; ECO, organic; HFW, haulm fresh weight; LI, internode length; LPS, length of primary shoots; MLS, mature leaf size; NI, number of internodes; NL, number of leaves per plant; NMRPP, number of marketable roots per plant; NRPP, number of storage roots per plant; PE, polyethylene mulch; PL, petiole length; PSN, primary shoot number; RD, root diameter; RL, root length; Soil, bare soil; TWRPP, total root weight per plant; WMR, weight of marketable roots per plant.

ketable storage roots (0.921), total weight of storage roots (0.920), weight of marketable roots (0.892), LPS (0.881), internode diameter (0.840), HFW (0.804), RD (0.729), and RL (0.697). This axis represents overall plant productivity, integrating both vegetative vigor and storage root yield components, with higher PC1 scores indicating superior agronomic performance. PC2 captured a pronounced ecological trade-off between vegetative growth and storage root development. Traits associated with shoot architecture loaded positively on PC2, including number of leaves (0.653), PL (0.534), mature leaf size (0.452), HFW (0.423), and number of internodes (0.339). In contrast, yield-related traits exhibited consistently negative loadings on this axis, particularly RL (−0.570), RD (−0.528), weight of marketable roots (−0.345), number of marketable roots (−0.323), and total storage root weight (−0.283). This opposing pattern along PC2 reflects the physiological trade-off between investment in above-ground vegetative structures and below-ground storage organ development—a fundamental source-sink relationship in sweetpotato production. The PCA biplot (Figure 4) revealed clear separation of treatment combinations along the principal component axes. Growing season had a pronounced effect on multivariate trait profiles, with 2022 treatments shifted toward higher PC1 scores (mean PC1: 1.27) compared to 2021 (mean PC1: −0.87), indicating superior overall agronomic performance in the second year (Table S4). Cultivation method also strongly influenced multivariate positioning: PE treatments showed substantially higher PC1 scores (mean: 1.31) than bare soil (mean: −0.91), confirming the positive effect of mulching on productivity-related traits. The 95% confidence ellipses demonstrated clear separation between years (solid lines) and between mulch types (dashed lines), with minimal overlap, indicating that these factors consistently differentiate the multivariate trait profiles.

Varietal performance was strongly differentiated along both axes. Martina showed the highest PC1 values among all varieties (mean: 1.83), confirming its superior yield potential across management systems. This was especially evident under PE in 2022, where Martina achieved the maximum PC1 scores of 5.77 (conventional) and 5.54 (organic). Lučka had the most negative PC2 values (mean: −1.46), indicating a stronger association with yield traits relative to vegetative growth. In contrast, Janja (mean PC1: −1.27) and Purple Speclet (mean PC1: −0.38; mean PC2: 1.36) clustered at lower PC1 values, reflecting comparatively lower yield performance. The lowest PC1 score overall (−5.28) was recorded for Janja under organic management on bare soil in 2021, highlighting the combination of factors least favorable for productivity. The most favorable treatment combinations were from the 2022 growing season under PE. Martina under both conventional (PC1: 5.77) and organic (PC1: 5.54) management clustered in the region of highest PC1 scores, showing strong positive associations with yield-related traits. Lučka under conventional management with PE in 2022 also performed well (PC1: 2.98), though its more negative PC2 score (−2.60) indicates a stronger yield focus relative to vegetative growth. Purple Speckle under organic management with PE in 2022 showed the highest PC2 score (2.90) among 2022 treatments, reflecting proportionally greater vegetative development. These results demonstrate that PEing was associated with higher PC1 scores across all varieties and years, while bare soil consistently resulted in lower PC1 scores. The separation of varieties along PC1 and the opposing loadings on PC2 highlight distinct genotypic patterns in the relationship between vegetative growth and storage root yield.

4 | DISCUSSION

This study highlights the complex interplay of genetic, environmental, and management factors in determining the vegetative growth and storage root yield of sweetpotato, emphasizing the significant influence of variety, cultivation method, and seasonal variation. The pronounced varietal effects, which accounted for the largest proportion of variance in these traits, demonstrate the fundamental importance of genetic factors. The strong influence of variety on LI, PL, leaf size, RD, and RL indicates that these parameters are under significant genetic control, consistent with studies reporting high heritability for these traits in sweetpotato (Gupta et al., 2020; Verma et al., 2023).

The superior yield performance of Martina across all management systems aligns with recent genomic studies identifying genetic markers linked to starch metabolism and stress tolerance. This finding is consistent with genome-wide association studies by Haque et al. (2023), which identified single-nucleotide polymorphisms associated with starch content and genes involved in starch metabolism, such as granule-bound starch synthase I. Similarly, Nie et al. (2023) identified genes related to sugar and starch metabolism that influence storage root development. Martina's consistent performance across diverse management systems reflects robust stress tolerance mechanisms, a trait highly valued in breeding programs. This interpretation is supported by studies on sweetpotato stress tolerance, including Zhang et al. (2023), who identified DNA-binding one-finger (Dof) transcription factors with expression changes under drought and salt stress, and Cheng et al. (2024), who demonstrated that overexpression of IbDHAR1 enhances antioxidant enzyme activity and stress tolerance. In contrast, Janja and Purple Speclet exhibited distinct morphological characteristics, with especially vigorous vegetative growth indicated by greater haulm biomass. A similar pattern was observed in the African variety Ejumula, which has orange-colored flesh (Ramírez et al., 2017). According to Peters (2015), varieties that prioritize above-ground biomass production over storage root development are valuable for sweetpotato cultivation, especially as livestock feed. This growth pattern can be strategically managed through nitrogen and water applications that promote vegetative development (Gajanayake, Raja Reddy, Shankle, Arancibia, et al., 2014).

Recent studies have shown that the balance between vegetative growth and storage root development in root crops is influenced by the interaction of management practices, environmental factors, and genetic regulation (Gajanayake, Raja Reddy, Shankle, Arancibia, et al., 2014; Hoang et al., 2020). In our study, the cultivation method was crucial, with PE significantly improving both growth and yield parameters. The substantial increase in biomass production under PE represents a marked improvement in resource utilization. According to Shi et al. (2022), PE affects soil properties by adsorbing potassium and phosphorus, lowering pH, and increasing electrical conductivity and temperature, which together enhance growth parameters and yield components in sweetpotato (Krochmal-Marczak et al., 2018; Rao et al., 2023; Sapakhova et al., 2024). Furthermore, PE has been shown to improve not only yield but also nutritional quality, including increased levels of monosaccharides, disaccharides, anthocyanins, starch, vitamin C, total phenolic compounds, and antioxidant potential (Hou et al., 2019; Sapakhova et al., 2024; Sinkovič et al., 2024).

The growing season significantly influenced sweetpotato performance, with a greater effect on yield-related traits than on vegetative parameters. Temperatures in both seasons were within ranges considered favorable for sweetpotato growth (Mulovhedzi et al., 2020), and rainfall was generally adequate. The contrasting patterns between 2021 and 2022 provide important insights into environmental adaptation. While storage root number formation was favored in 2021, storage root weight parameters improved markedly in 2022. These differences are largely attributable to precipitation patterns, with substantially higher rainfall in 2021 (1267 mm) than in 2022 (966 mm). Rainfall critically influences storage root formation and development, as sweetpotato requires optimal soil moisture (Gajanayake, Raja Reddy, Shankle, Arancibia, Villordon, et al., 2014). Uniformly moist soils provide the best environment, while excessive rainfall, as observed in 2021, can limit oxygen availability, reduce photosynthetic efficiency, and constrain nutrient uptake, favoring storage root number over weight gain (Shah et al., 2023). Conversely, moderate rainfall in 2022 provided favorable moisture levels for better root oxygenation and nutrient uptake, which are essential for achieving greater storage root weights (C. Wang et al., 2024). The significant Year × Cultivation Method interaction highlights the need to adapt management practices to specific seasonal conditions, supporting the value of climate-adapted agricultural practices (Abrham et al., 2021).

The impact of the cropping system was modest compared to other factors but revealed significant patterns for sustainable production. Conventional systems produced higher total and marketable storage root weights than organic systems, consistent with meta-analyses across various crops (Seufert et al., 2012) and studies specific to sweetpotato (Nwosisi et al., 2021). Similar trends have been reported for potato (Ierna & Parisi, 2014; Zarzyńska & Pietraszko, 2015) and wheat (J. Wang et al., 2020). These outcomes are expected, as conventional agriculture benefits from synthetic fertilizers, herbicides, and pesticides, which increase yields by about 20% compared to organic methods (de la Cruz et al., 2023). For sweetpotato, lower organic yields are attributed to weed pressure (Nwosisi et al., 2021) and suboptimal nutrient availability (Darko et al., 2020). However, the relatively small differences between systems suggest opportunities to optimize organic production. Notably, under PE in 2022, the most favorable conditions observed, the total storage root weight difference between conventional and organic systems narrowed considerably, supporting the approximately 11% overall yield gap reported here and suggesting that mulching can substantially compensate for yield-limiting constraints in organic management. The significant Y × CS interaction for storage root number indicates that system efficiency strongly depends on seasonal conditions. Margus et al. (2022) found that organic farming combined with cover crops and appropriate fertilization can achieve yields comparable to conventional systems under certain conditions, while Ierna and Parisi (2014) reported yield differences ranging from 5% to 50% across seasons.

The exceptionally strong positive correlations among storage root yield components indicate close physiological integration, consistent with shared regulatory mechanisms for carbohydrate partitioning and assimilate allocation during storage root development, as proposed in the literature. These findings are in agreement with previous studies on sweetpotato (Alam et al., 2023; Yahaya et al., 2015). This synchronized development may reflect regulation by common genetic networks controlling assimilate allocation efficiency, as yield is the cumulative outcome of source-sink dynamics for photoassimilates and nutrients throughout development (Smith et al., 2018). Therefore, selection for improved sink strength in one component may result in coordinated improvements across yield parameters through enhanced source-sink relationships.

The strong positive correlations between root morphology (diameter, length) and yield components highlight the importance of storage root architecture in determining productivity potential. These relationships are consistent with the physiological principle that storage root enlargement depends on sustained assimilate supply and starch accumulation capacity during the filling period, with molecular regulatory mechanisms involving complex metabolic processes (Alam et al., 2024). Integrated transcriptome and metabolome studies suggest that radial and longitudinal root growth are coordinated through common developmental pathways involving cell expansion, division, and metabolic regulation (Wu et al., 2024). Improving these traits may enhance productivity, storability, and market value.

Primary shoot length showed a moderate positive correlation with HFW, and both traits correlated moderately with storage root yield components, suggesting that vegetative architecture is associated with reproductive success. Enhanced shoot growth increases photosynthetic surface area and may improve nutrient and water uptake, potentially supporting subsequent storage root development (Adubasim et al., 2017). This supports the principle that shoot vigor is associated with greater sink activity under favorable agronomic conditions (Alam et al., 2023; Kathabwalika et al., 2016). The correlation between LPS and yield components is consistent with improved root-shoot coordination, as source-sink relationships determine crop yield and are largely regulated by water and nutrient availability (Li et al., 2016). This vegetative-reproductive coupling suggests that investment in above-ground biomass may create positive feedback, improving resource acquisition and supporting increased storage root development.

The physiological basis of these correlations may involve plant regulation of carbon flux during storage root formation, with metabolism organized into source and sink compartments that communicate through coordinated transport mechanisms. As reviewed by Jiang et al. (2024), starch synthesis in chloroplasts, photoassimilate transport from source to sink, and starch accumulation in sink tissues require highly regulated networks that respond to environmental conditions. These relationships are consistent with studies showing that optimizing vegetative traits, particularly shoot architecture and leaf development, can improve both vegetative vigor and reproductive performance by enhancing resource acquisition and utilization (Alam et al., 2023; Kathabwalika et al., 2016). The integrated nature of these correlations suggests that breeding strategies targeting varieties with coordinated vegetative and reproductive traits may be beneficial, as improvements in canopy development could result in proportional increases in storage root yields through enhanced physiological efficiency.

Principal component analysis revealed clear separation between growing environments based on cultivation methods, with PE treatments positively associated with vegetative growth and yield parameters. Similar results were reported by Shrestha and Miles (2022), who observed higher soil temperatures and sweetpotato yields under plastic mulch compared with bare soil. The observed trade-off between vegetative growth and yield components highlights complex resource allocation mechanisms, consistent with established understanding of source-sink relationships in root crops. According to Zierer et al. (2021), reduced shoot growth limits photosynthetic capacity and the resources available for storage organ development, while insufficient storage sinks can lead to feedback inhibition of photosynthesis, a protective mechanism that may reduce photosynthetic efficiency, biomass production, and yield.

The PCA results also revealed significant three-way interactions among year, cropping system, and cultivation method in determining variety performance. Martina showed outstanding performance, particularly under PE in 2022, which may be attributed to the synergistic effects of increased soil temperature and improved moisture retention provided by PE (Shrestha & Miles, 2022). In contrast, Janja and Purple Speclet had lower yield performance under the same conditions, indicating genotype-specific plasticity in resource utilization, as documented by Oljača et al. (2018). These findings have important implications for sweetpotato cultivation strategies. The effectiveness of PE mulch in enhancing vegetative growth and storage root yield, especially under favorable environmental conditions, suggests its potential for intensive production systems. However, the significant interactions observed among variety, environment, and management highlight the need for tailored cultivation approaches, with variety selection based on local conditions and management practices.

Several limitations should be considered when interpreting these findings. First, the study was conducted at a single location over two growing seasons, which limits generalizability to other temperate regions with different soil types, climatic patterns, or daylength regimes. Multi-location trials across a broader range of environments would strengthen conclusions about genotype × season and genotype × management interactions. Second, the four varieties evaluated, while representing diverse flesh colors and growth habits, constitute a limited sample of sweetpotato germplasm; inclusion of additional genotypes would further elucidate the genetic basis of observed responses. Third, direct physiological measurements (photosynthetic rates, stomatal conductance, and nutrient uptake dynamics) were not assessed, so mechanistic interpretations of source-sink relationships remain correlative rather than causal. Fourth, while PE proved highly effective, its environmental sustainability is a concern; future research should evaluate biodegradable alternatives and organic mulches to balance productivity with ecological considerations.

5 | CONCLUSIONS

This study demonstrates that sustainable intensification of sweetpotato production in temperate climates is achievable by strategically aligning genotype selection with adapted management practices. The most significant finding is not the expected superiority of conventional systems, but that organic production with PE reduced the yield gap to approximately 11%. This reframes the agronomic question from whether organic sweetpotato production is feasible to under which conditions it becomes competitive, with direct implications for producers considering sustainability transitions. The source-sink framework revealed by PCA provides the mechanistic basis for these recommendations. Martina's dominance across management systems reflects a resource allocation strategy that PE further enhances by improving soil thermal and moisture conditions, explaining why this genotype-management combination consistently achieved peak multivariate performance. This convergence establishes a reproducible framework for identifying similarly adapted genotypes in future screening programs and demonstrates that multivariate trait profiling captures productivity dynamics that univariate analyses of individual yield components often obscure. Several limitations define the direction for future research. The single-location, two-season design limits generalizability across the climatic and edaphic diversity of temperate agroecosystems, and the four-variety panel restricts conclusions about broader genetic diversity in source-sink partitioning. The mechanistic interpretation of trade-offs remains correlational and requires physiological validation. Critically, the environmental costs of PE—microplastic contamination, disposal burden, and carbon footprint—were not quantified and must be addressed before unconditional recommendation. Future work should therefore prioritize multi-environment trials, biodegradable mulch alternatives, and life-cycle assessment to reconcile the productivity gains demonstrated here with long-term ecological sustainability.

AUTHOR CONTRIBUTIONS

Mohamed Neji: Conceptualization; formal analysis; writing—original draft. **Vladimir Meglič**: Conceptualization; writing—review and editing. **Nataša Kunstelj**: Investigation; writing—original draft. **Barbara Pipan**: Conceptualization; data curation; writing—review and editing. **Lovro Sinkovič**: Conceptualization; formal analysis; investigation; supervision; writing—review and editing.

ACKNOWLEDGMENTS

This study was funded by grants from The Slovenian Research and Innovation Agency (ARIS), Ljubljana, Slovenia, entitled "Agrobiodiversity" (P4-0072). The authors would like to thank Dragan Žnidarčič and the Biotechnical Faculty of the University of Ljubljana for their support in providing plant material for the study.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data generated or analyzed during this study are included in the manuscript.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Neji, M., Meglič, V., Kunstelj, N., Pipan, B., & Sinkovič, L. (2026). Genotype, mulching, and cropping system interactions drive vegetative growth and storage root yield in temperate-grown sweetpotato. *Crop Science*, *66*, e70303. https://doi.org/10.1002/csc2.70303