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Sequential foliar NPK nutrition and amino acid supplementation mitigate plant-available water deficit effects on growth, yield, and tuber carbohydrates of potato under greenhouse conditions

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Abstract

Water deficit is a major constraint for potato (*Solanum tuberosum* L.) production, reducing canopy development, tuber filling, and quality-related carbohydrate accumulation. Foliar nutrition and amino-acid-based biostimulants may partially offset drought-induced limitations in root nutrient uptake and plant metabolic activity. This greenhouse pot experiment evaluated whether a phenology-based, sequential foliar nutrition program and amino acid supplementation can alleviate the effects of progressive reductions in plant-available water (PAW) on potato growth, yield, and tuber carbohydrate composition. Certified seed tubers of cv. Agria were grown in clay loam soil under a completely randomized design with three replications. Pots were maintained at four PAW regimes (100%, 75%, 50%, and 25%), with three foliar regimes within each PAW level: (i) non-sprayed control, (ii) sequential foliar fertilization, and (iii) sequential foliar fertilization plus amino acids. Foliar applications were conducted four times from early vegetative growth to tuber bulking, using stage-specific water-soluble NPK formulations supplemented with micronutrients; the amino acid product was applied concomitantly in the combined treatment. Decreasing PAW reduced stem number, stem diameter, plant length, total leaf number, tuber yield, and tuber carbohydrate concentrations. Across irrigation regimes, sequential foliar fertilization improved vegetative growth and increased tuber yield relative to the control, and amino acids provided a further benefit. Yield responses exceeded changes in tuber number, indicating effects mainly on tuber growth rather than tuber set. Foliar treatments—particularly with amino acids—also increased tuber glucose, fructose, sucrose, and starch within each PAW level, suggesting improved carbon assimilation and/or sink activity under water limitation. Overall, a stage-targeted foliar NPK program integrated with amino acids is a practical strategy to reduce yield penalties and sustain tuber carbohydrate accumulation under deficit irrigation. Field validation across cultivars and mechanistic measurements are warranted to refine dose-timing recommendations.

Keywords: Potato, deficit irrigation, foliar fertilization, amino acids, tuber carbohydrates.

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Introduction

Potato (*Solanum tuberosum* L.) is one of the most important food and industrial crops worldwide, supplying carbohydrates and energy while supporting diverse processing chains such as frying and starch-based



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products. Achieving stable yield and tuber quality depends strongly on the interaction between water availability and nutrient supply, particularly during canopy development and tuber bulking. Optimized mineral fertilization has been repeatedly shown to enhance potato growth, physiological performance, and tuber yield, whereas inadequate nutrition reduces leaf area development, biomass accumulation, and yield potential under both greenhouse and field conditions (Martins et al., 2018; Petropoulos et al., 2020; Chabani et al., 2024).

In many potato-growing regions, however, water scarcity and irregular rainfall increasingly constrain production. Deficit irrigation and drought stress commonly reduce canopy expansion, limit photosynthetic capacity, and decrease assimilate allocation to tubers, causing lower marketable yield and altered quality traits (Man-Hong et al., 2020; Acevedo et al., 2023). Under greenhouse or other controlled environments, these constraints can be investigated with greater precision because field-scale heterogeneity is minimized; accordingly, resource limitation (especially N and water) has been shown to reduce chlorophyll status, biomass, and yield under controlled conditions (Chabani et al., 2024; Barandalla et al., 2025). Beyond yield quantity, water deficit may also affect carbohydrate metabolism and storage, thereby influencing soluble sugars and starch accumulation in tubers, which are central to processing quality.

Balanced fertilization can partially compensate for stress impacts by sustaining plant nutrition and canopy function. Several authors have emphasized that potato has high nutrient demand, and that appropriate NPK management is critical for maximizing growth and yield; at the same time, excessive fertilization may not proportionally increase yield and may increase environmental burdens, highlighting the need for efficient nutrient strategies (Abewoy, 2024; Chabani et al., 2024; Seno Nascimento et al., 2024). In addition to soil fertilization, foliar nutrient supply is increasingly considered a practical approach—particularly under drought—because root uptake may be restricted by reduced mass flow and diffusion, and leaf-applied nutrients can support canopy metabolism more directly (Horvat et al., 2010; Wadas, 2021). Earlier work by Horvat et al. (2008) and Horvat et al. (2010) showed that foliar fertilization can maintain physiological status and protect yield under water stress conditions, supporting the concept that foliar feeding is an effective “bridge” strategy when soil water limits nutrient acquisition.

Alongside foliar fertilization, a wide range of foliar-applied biostimulants and protective compounds have been tested to mitigate drought impacts in potato. For example, Man-Hong et al. (2020) reported that foliar-applied water-soluble humic substances improved photosynthetic characteristics and tuber yield under different water deficits. Other studies demonstrated that foliar-applied silicon can enhance potato growth under stress (Wadas, 2021), while exogenous applications such as salicylic acid, melatonin-related approaches, and chitosan-based strategies can strengthen stress resilience by reducing oxidative damage and improving physiological stability (Desoky et al., 2021; Morovvat et al., 2021; El-Yazied et al., 2022; Acevedo et al., 2023). Moreover, more recent work indicates that foliar ZnO and SiO₂ nanoparticles can improve morphological and biochemical traits and enhance yield and water-use efficiency under water deficit (Al-Selwey et al., 2023; Seleiman et al., 2023). Collectively, these studies indicate that foliar interventions can operate through multiple pathways—maintenance of chlorophyll and photosynthesis, improved leaf water relations, and stress-protective antioxidant responses—thereby supporting carbon assimilation and tuber filling under drought.

Controlled-environment studies also show that foliar programs applied at key phenological stages can measurably improve crop productivity and nutrient status, supporting the concept that “timing” is integral to the success of foliar interventions. For example, Islamzade et al. (2025) reported that foliar fertilization in wheat under greenhouse conditions increased yield and grain nutrient composition, with the most efficient outcomes achieved when applications targeted the tillering and stem elongation stages rather than later sprays alone. Likewise, earlier evidence emphasized that under dry conditions, nutrients may be present in soil yet become less available to plants, and supplementary foliar nutrition can therefore provide a practical route to sustain reproductive filling processes (Gülser et al., 2019). Beyond mineral nutrition, biostimulant-oriented foliar strategies (e.g., amino acids and seaweed extracts) have been shown to enhance canopy vigor, yield components, and nutrient uptake under abiotic stress scenarios, indicating that combined foliar inputs may strengthen plant resilience and resource-use under constrained environments (Zhussupova et al., 2026). Evidence from horticultural systems also points in the same direction: foliar biostimulant and micronutrient complexes improved yield and fruit biochemical quality in tomato, illustrating the broader potential of foliar biostimulant concepts to enhance productivity where resource efficiency is targeted (Aitbayev et al., 2025).

Foliar amino acids and amino-acid-based biostimulants represent another promising tool for improving potato performance under suboptimal conditions. Many reports show that foliar amino acids enhance vegetative growth, nutrient status, and yield or marketable yield, and can improve tuber quality traits such as

dry matter, starch, carbohydrates, and protein (Shaheen et al., 2019; Samy, 2022; Kuznetsova et al., 2022; Mahmoud et al., 2023; Saaseea and Al-A'mry, 2024; Zeebaree and Mohammed, 2025). Mahmoud et al. (2023), for instance, documented that tryptophan and its derivatives can stimulate growth, yield, and tuber quality, whereas Kuznetsova et al. (2022) reported increased marketable yield fraction after foliar application of an amino-acid-based stimulator. A broader synthesis by Henderson et al. (2025) emphasizes that amino acids can act as biostimulants, yet responses are strongly dependent on dose, timing, and plant status—underscoring the need to test amino acids within clearly defined water and nutrient regimes.

Despite this progress, a practical gap remains in linking graded water limitation levels with stage-targeted foliar nutrient programs and amino acid supplementation in a single, integrated framework. Many studies focus on single compounds, single stress levels, or one-time applications; fewer studies evaluate a phenology-based, sequential foliar nutrition schedule aligned with key developmental stages under systematically controlled soil moisture (PAW) gradients. In addition, the combined effects of foliar nutrient programs and amino acids on tuber carbohydrate composition (soluble sugars and starch), which is directly relevant to processing quality, remain relatively underreported under controlled PAW deficit scenarios.

Therefore, the objective of this study was to determine whether a sequential foliar nutrition program (balanced NPK formulations supplemented with micronutrients) applied at key phenological stages—alone or combined with an amino-acid product—can mitigate the negative effects of progressive PAW reduction on (i) potato growth traits, (ii) tuber yield and tuber number, and (iii) tuber carbohydrate composition (glucose, fructose, sucrose, and starch) under greenhouse pot conditions. We hypothesized that decreasing PAW would reduce growth, yield, and carbohydrate accumulation, while foliar nutrition would partially offset these reductions and that amino acid supplementation would provide an additional benefit through improved nutrient assimilation and stress resilience mechanisms documented in the literature (Desoky et al., 2021; Mahmoud et al., 2023; Acevedo et al., 2023).

Material and Methods

Plant and Soil Materials

Certified seed tubers of Agria potato (*Solanum tuberosum* L.), a cultivar widely used for industrial frying, were used as the plant material. For each treatment, the required number of seed tubers was selected to ensure size uniformity; tubers with an approximate transverse diameter of 45–50 mm and a fresh weight of 70–75 g were used. Selected tubers were pre-sprouted in a controlled-environment chamber at 25 ± 1 °C for 20 days and subsequently used in the greenhouse experiment.

A clay loam soil was used as the growing medium. Soil texture was determined by the hydrometer method (Bouyoucos, 1951). Field capacity and permanent wilting point were determined using a pressure plate apparatus (Richards pressure plate) (Cassel and Nielsen, 1986). Soil pH was measured in a 1:1 soil-to-water suspension using a pH meter (Peech, 1965), and electrical conductivity (EC) was measured in a 1:1 soil-to-water extract (Rowell, 1996). Organic matter content was determined by the Walkley-Black method (Walkley and Black, 1934), while total carbonate content was analyzed using the Scheibler calcimeter (Loeppert and Suarez, 1996).

Experimental Design and Greenhouse Conditions

The experiment was conducted in a greenhouse between 15 March 2024 and 15 June 2024, using a completely randomized design with three replications. Agria tubers were planted in cylindrical plastic pots (25 cm diameter; 5 L volume). The growing medium consisted of 4.5 kg of clay loam soil, sieved through a 4-mm mesh. One seed tuber was planted per pot.

Prior to planting, 100 mL of Hoagland nutrient solution was applied to each pot, and no additional fertilization was provided thereafter. The plant-available water (PAW) capacity of the clay loam soil used in the experiment was calculated as 15.05% (Table 1). Based on this value, pot moisture contents were adjusted to 27.15%, 23.39%, 19.62%, and 15.86% to represent 100%, 75%, 50%, and 25% PAW irrigation regimes, respectively. Until harvest, pots were weighed at two-day intervals, and the amount of water lost was replenished with distilled water to maintain the target moisture contents corresponding to the 25%, 50%, 75% and 100% PAW levels.

Foliar Applications

Foliar spray applications were performed four times, using a spray volume equivalent to 50 L water per decare. The first application was performed at the 3–5 leaf stage, the second at the pre-flowering stage, the third at the onset of tuber bulking, and the fourth during the tuber bulking stage. The following water-soluble foliar fertilizers were applied at a dose of 500 g per 100 L:

- (i) 19-9-9 + 2MgO + micronutrients (first application),
- (ii) 9-30-9 + 2MgO + micronutrients (second application),
- (iii) 17-17-17 + micronutrients (third application), and
- (iv) 9-9-25 + 2MgO + micronutrients (fourth application).

As an amino acid source, an animal-derived amino acid product containing 55% organic matter, 45% total amino acids, and 12% free amino acids was applied at 150 mL per 100 L.

Treatments

- T1 : 100% PAW
- T2 : 100% PAW + foliar fertilizer
- T3 : 100% PAW + foliar fertilizer + amino acids
- T4 : 75% PAW
- T5 : 75% PAW + foliar fertilizer
- T6 : 75% PAW + foliar fertilizer + amino acids
- T7 : 50% PAW
- T8 : 50% PAW + foliar fertilizer
- T9 : 50% PAW + foliar fertilizer + amino acids
- T10 : 25% PAW
- T11 : 25% PAW + foliar fertilizer
- T12 : 25% PAW + foliar fertilizer + amino acids

Plant Growth Assessment

To examine the effects of the irrigation regime and foliar applications on potato growth, several morphological traits were recorded at the end of the vegetative growth and sprouting phase. These included stem number per plant (SN) and mean stem diameter (SD), measured at the midpoint of the main stem using a calliper (cm), as well as plant length (PL) relative to the main stem (cm) and the total leaf number per plant (TLN) (Geiger et al., 1996).

Yield and Yield Components

At the completion of the experiment (120 days after planting), tubers were hand-harvested separately for each treatment and replicate. Harvested tubers were subsequently counted and weighed with an electronic balance.

Total Soluble Sugar Determination

At harvest, mature leaf samples (100–150 g fresh weight) and tubers (200 g fresh weight) were collected, immediately frozen in liquid N, and stored at sunset to capture the period when soluble sugars in source leaves are expected to be highest (Chincinska et al., 2008). For extraction, samples were incubated in 1 mL of 80% ethanol at 80 °C for 2 h. The resulting supernatant was used to determine total soluble sugars (glucose, fructose, and sucrose). The pellet was rinsed three times with 80% ethanol and then dried at 70 °C. Leaf and tuber tissues were homogenized in 800 µL of 0.2 M KOH and heated at 95 °C for 1 h. The extract pH was adjusted to neutral to slightly acidic with 140 µL of 1 M acetic acid, followed by centrifugation for 5 min (10,000× g). An aliquot (~50 µL) of the supernatant was combined with 100 µL amyloglucosidase (2 mg/mL in 50 mM sodium acetate buffer, pH 5.0) and incubated overnight at 55 °C. Sugars were quantified using sucrose standards, and concentrations were expressed as mg g⁻¹ fresh weight.

Starch Content Evaluation

Starch was quantified following the protocol of Berry and Bjorkman (1980). The residue remaining after total soluble sugar (TSS) extraction was dried at 70 °C, after which starch was hydrolysed with 52% perchloric acid for 30 min and centrifuged for 10 min (2000× g). This hydrolysis step was repeated three times, supernatants were pooled, and starch was determined using the phenol-sulphur assay (Norwitz et al, 1981). Starch content was reported as mg g⁻¹ fresh weight.

Results

Soil physicochemical characteristics of the experimental soil

The physicochemical properties of the soil used as the growth medium are presented in Table 1. The soil had a clay loam texture (sand 28.90%, silt 40.80%, clay 30.30%), with a field capacity of 27.0% and a permanent wilting point of 12.0%, resulting in a plant-available water content of approximately 15.0%. The soil reaction was near neutral to slightly alkaline (pH 7.30), and the EC value was low (0.48), indicating a non-saline growing medium. Organic matter content was 1.94%, suggesting low organic matter status, whereas CaCO₃ content (13.04%) indicated a calcareous soil condition (Table 1).

Table 1. Physicochemical properties of the experimental soil used as the growing medium (clay loam).

Property	Unit	Value
Sand	%	28.90
Silt	%	40.80
Clay	%	30.30
Texture class	–	Clay loam
Field capacity	% (w/w)	27.00
Permanent wilting point	% (w/w)	12.00
Plant-available water (PAW)	% (w/w)	15.00
pH (1:1 soil:water)	–	7.30
EC (1:1 soil:water)	dS m ⁻¹	0.48
Organic matter	%	1.94
CaCO ₃	%	13.04

Plant Growth Traits

Across all treatments, decreasing plant-available water (PAW) from 100% to 25% resulted in consistent reductions in stem number (SN; stems plant⁻¹), mean stem diameter (SD; mm), plant length (PL; cm), and total leaf number (TLN; leaves plant⁻¹) (Figure 1). Under 100% PAW, foliar nutrition and amino acid supplementation improved growth relative to the control: SN increased from 2.96 stems plant⁻¹ (T1) to 3.42 stems plant⁻¹ (T2) and 3.60 stems plant⁻¹ (T3), SD increased from 7.95 mm (T1) to 8.53 mm (T2) and 8.62 mm (T3), PL increased from 25.64 cm (T1) to 28.13 cm (T2) and 31.12 cm (T3), and TLN increased from 39.69 leaves plant⁻¹ (T1) to 41.15 leaves plant⁻¹ (T2) and 42.05 leaves plant⁻¹ (T3) (Figure 1a–d). Under 75% PAW, the same pattern was maintained, with values improving from 2.83–3.31 stems plant⁻¹ for SN, 6.92–8.16 mm for SD, 24.36–26.69 cm for PL, and 35.75–41.26 leaves plant⁻¹ for TLN (T4–T6), indicating mitigation of moderate water deficit by foliar fertilizer and amino acids (Figure 1). Under 50% PAW, reductions in leaf development were pronounced, yet foliar fertilizer plus amino acids increased TLN from 20.50 leaves plant⁻¹ (T7) to 29.48 leaves plant⁻¹ (T9), alongside increases in SN (2.13 to 2.93 stems plant⁻¹), SD (5.67 to 6.42 mm), and PL (21.52 to 24.13 cm) (T7–T9) (Figure 1a–d). Under 25% PAW, the lowest values were recorded overall; however, combined foliar fertilizer + amino acids (T12) increased SN from 1.65 to 2.12 stems plant⁻¹, SD from 4.48 to 5.69 mm, PL from 19.13 to 21.36 cm, and TLN from 15.22 to 19.25 leaves plant⁻¹ compared with the corresponding control (T10) (Figure 1). Overall, within each PAW level, the treatment ranking was generally control < foliar fertilizer < foliar fertilizer + amino acids, highlighting additive benefits of foliar nutrition and amino acid supply under both adequate and deficit irrigation conditions (Figure 1).

Yield and Tuber Number

Tuber yield (yield plant⁻¹; g plant⁻¹) and tuber number (tubers plant⁻¹) generally declined as plant-available water (PAW) decreased from 100% to 25% (Figure 2). Across irrigation regimes, foliar fertilizer and amino acid applications tended to attenuate yield losses and slightly increase tuber number within each PAW level (Figure 2a,b). Under 100% PAW, yield increased from 548 g plant⁻¹ in the control (T1) to 602 g plant⁻¹ with foliar fertilizer (T2) and reached 643 g plant⁻¹ when foliar fertilizer was combined with amino acids (T3); tuber number increased from 6.28 (T1) to 6.35 (T2) and 6.52 tubers plant⁻¹ (T3) (Figure 2a,b). Under 75% PAW, yield rose from 486 g plant⁻¹ (T4) to 578 g plant⁻¹ (T5) and 592 g plant⁻¹ (T6), while tuber number increased from 5.96 to 6.23–6.33 tubers plant⁻¹ (Figure 2). Under 50% PAW, yield increased progressively from 402 g plant⁻¹ (T7) to 426 g plant⁻¹ (T8) and 458 g plant⁻¹ (T9), accompanied by small increases in tuber number from 5.65 to 5.75–5.95 tubers plant⁻¹ (Figure 2a,b). Under 25% PAW, yields were 352 g plant⁻¹ (T10), 369 g plant⁻¹ (T11), and 394 g plant⁻¹ (T12), whereas tuber number increased slightly from 5.12 (T10) to 5.28 (T11) and 5.48 tubers plant⁻¹ (T12) (Figure 2). Overall, within each PAW level, the yield ranking followed control < foliar fertilizer < foliar fertilizer + amino acids (Figure 2a), whereas changes in tuber number were comparatively small (Figure 2b), suggesting that yield responses were primarily associated with tuber growth (size/biomass accumulation) rather than major shifts in tuber set.

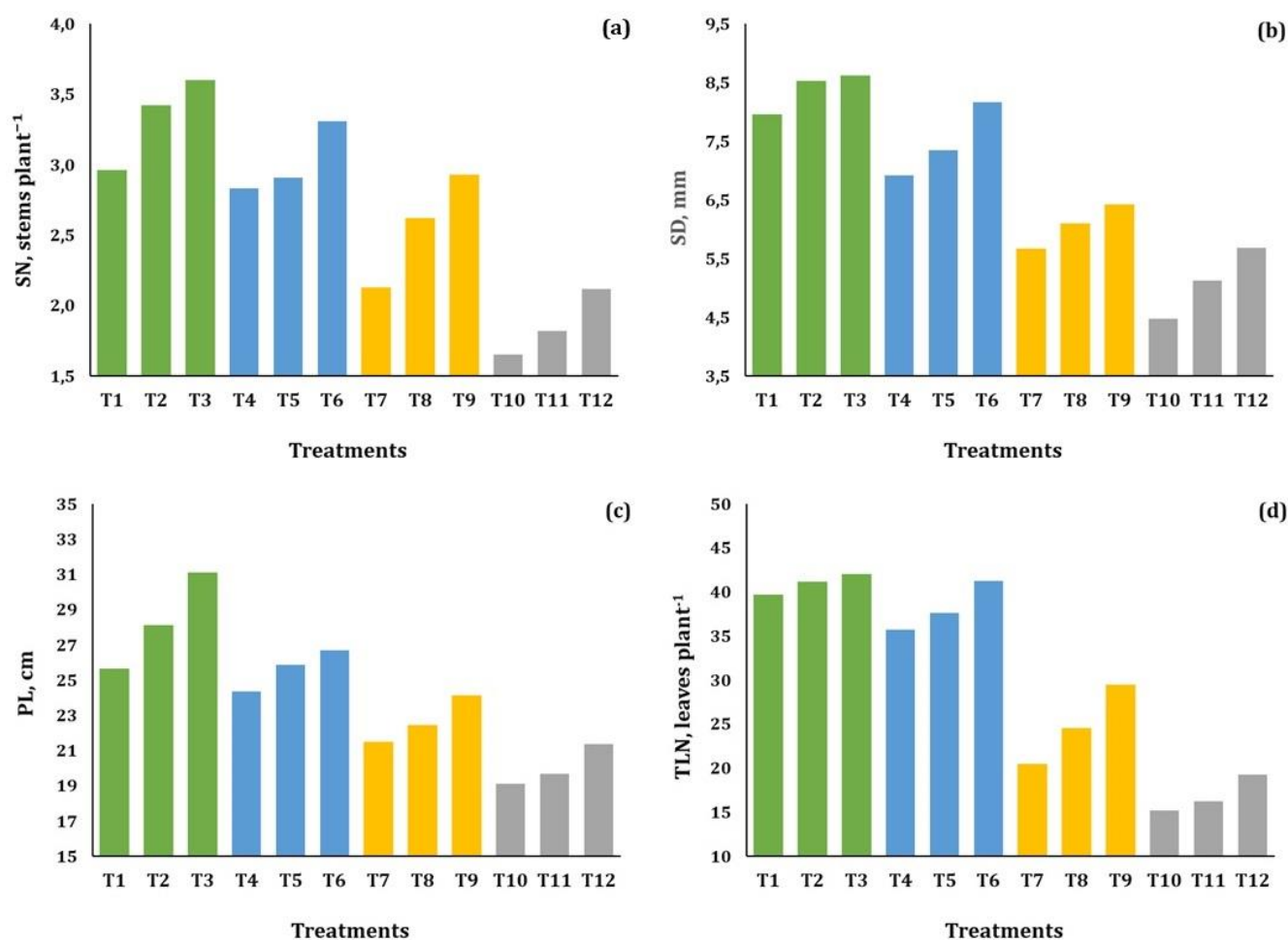


Figure 1. Effects of plant-available water (PAW) levels and foliar applications on potato growth traits. (a) stem number per plant (SN; stems plant⁻¹), (b) mean stem diameter (SD; mm), (c) plant length (PL; cm), and (d) total leaf number per plant (TLN; leaves plant⁻¹) across treatments. Treatments: T1 = 100% PAW; T2 = 100% PAW + foliar fertilizer; T3 = 100% PAW + foliar fertilizer + amino acids; T4 = 75% PAW; T5 = 75% PAW + foliar fertilizer; T6 = 75% PAW + foliar fertilizer + amino acids; T7 = 50% PAW; T8 = 50% PAW + foliar fertilizer; T9 = 50% PAW + foliar fertilizer + amino acids; T10 = 25% PAW; T11 = 25% PAW + foliar fertilizer; T12 = 25% PAW + foliar fertilizer + amino acids.

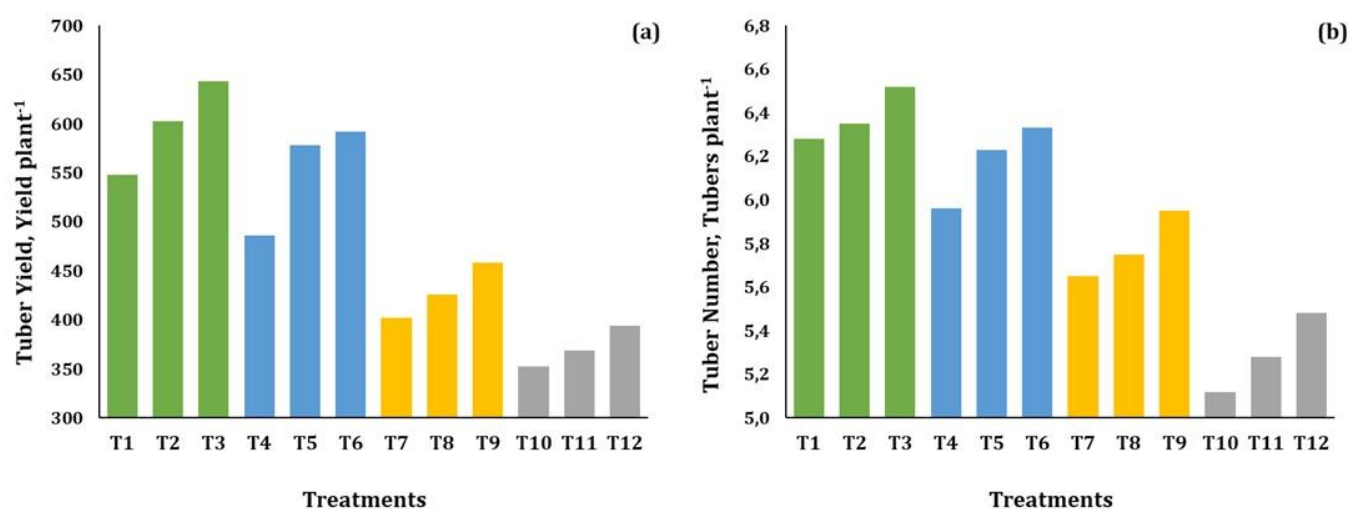


Figure 2. Effects of plant-available water (PAW) levels and foliar applications on tuber yield and tuber number in potato. (a) tuber yield (g plant⁻¹) and (b) tuber number (tubers plant⁻¹) across treatments (T1-T12). Treatments: T1 = 100% PAW; T2 = 100% PAW + foliar fertilizer; T3 = 100% PAW + foliar fertilizer + amino acids; T4 = 75% PAW; T5 = 75% PAW + foliar fertilizer; T6 = 75% PAW + foliar fertilizer + amino acids; T7 = 50% PAW; T8 = 50% PAW + foliar fertilizer; T9 = 50% PAW + foliar fertilizer + amino acids; T10 = 25% PAW; T11 = 25% PAW + foliar fertilizer; T12 = 25% PAW + foliar fertilizer + amino acids.

Tuber Carbohydrate Composition

Tuber carbohydrate concentrations generally decreased as plant-available water (PAW) declined from 100% to 25%, whereas foliar fertilizer and amino acid applications increased soluble sugars and starch within each PAW level (Figure 3). Across treatments, glucose, fructose, and sucrose are expressed as mg g^{-1} fresh weight (FW), and starch is also reported as mg g^{-1} FW. Under 100% PAW, glucose increased slightly from 1.83 mg g^{-1} FW (T1) to 1.85 mg g^{-1} FW (T2) and 1.90 mg g^{-1} FW (T3), while fructose increased from 1.09 to 1.10–1.12 mg g^{-1} FW; sucrose increased from 0.73 to 0.76–0.80 mg g^{-1} FW, and starch increased from 1.98 to 2.08–2.10 mg g^{-1} FW (T1–T3) (Figure 3a–d). Under 75% PAW, the same treatment ranking was maintained, with glucose increasing from 1.65 (T4) to 1.67 (T5) and 1.79 mg g^{-1} FW (T6), fructose from 0.93 to 0.98–1.08 mg g^{-1} FW, sucrose from 0.62 to 0.71–0.79 mg g^{-1} FW, and starch from 1.47 to 1.56–1.75 mg g^{-1} FW (T4–T6) (Figure 3). Under 50% PAW, water deficit markedly reduced carbohydrate contents; however, foliar fertilizer plus amino acids increased glucose from 0.95 (T7) to 1.16 (T8) and 1.23 mg g^{-1} FW (T9), fructose from 0.68 to 0.75–0.79 mg g^{-1} FW, sucrose from 0.45 to 0.48–0.56 mg g^{-1} FW, and starch from 0.82 to 0.88–1.08 mg g^{-1} FW (T7–T9) (Figure 3a–d). Under 25% PAW, the lowest values were recorded in the control (T10), with glucose, fructose, sucrose, and starch of 0.46, 0.40, 0.19, and 0.68 mg g^{-1} FW, respectively; nevertheless, combined foliar fertilizer + amino acids (T12) increased these values to 0.65, 0.67, 0.30, and 0.80 mg g^{-1} FW, respectively (Figure 3). Overall, within each PAW regime, the treatment sequence generally followed control < foliar fertilizer < foliar fertilizer + amino acids (Figure 3), indicating that foliar nutrition—particularly when combined with amino acids—helped sustain tuber soluble sugar and starch accumulation under progressive water deficit.

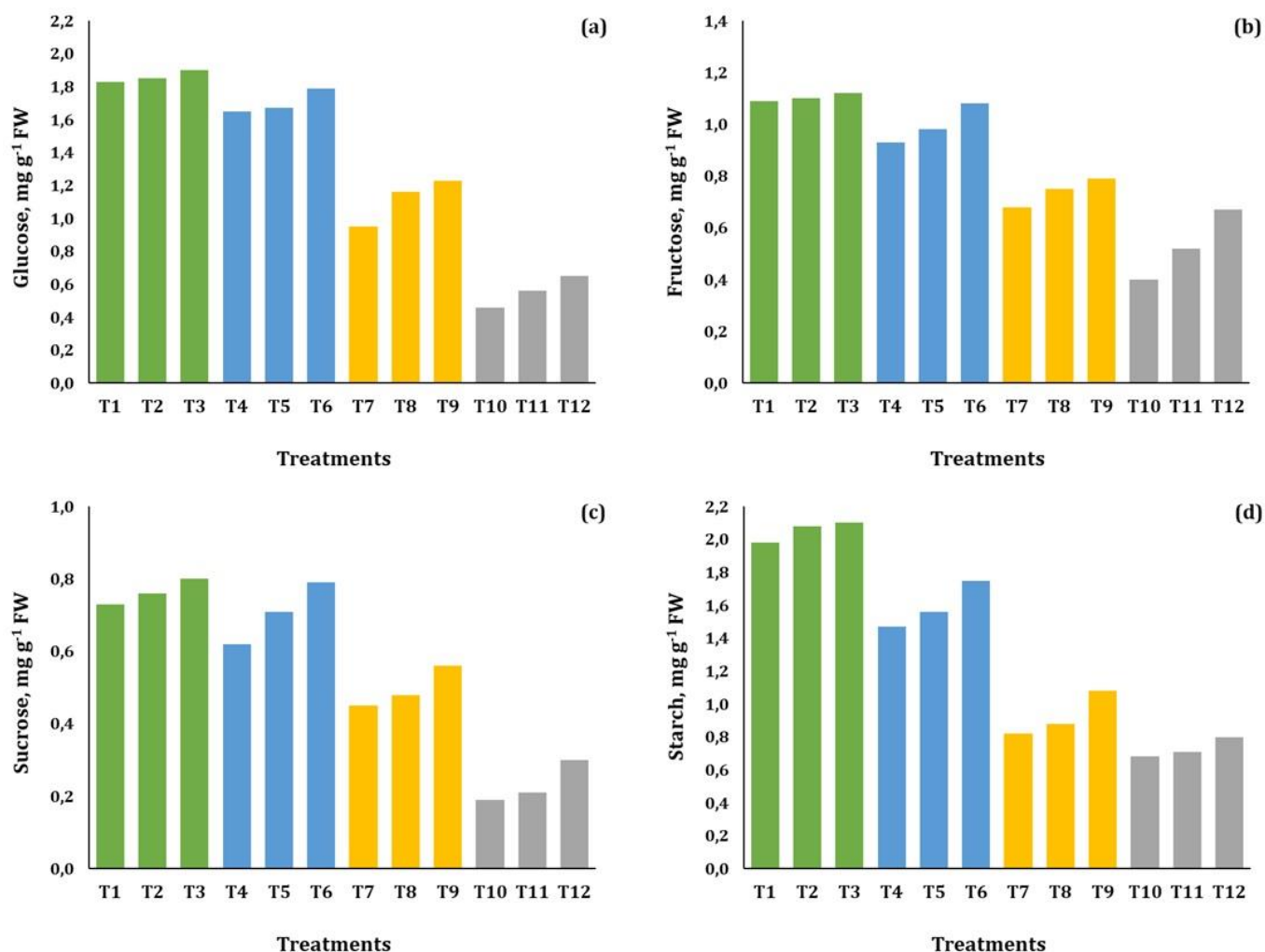


Figure 3. Effects of plant-available water (PAW) levels and foliar applications on tuber carbohydrate composition. (a) glucose, (b) fructose, (c) sucrose, and (d) starch concentrations in tubers (mg g^{-1} fresh weight, FW) across treatments (T1–T12). Treatments: T1 = 100% PAW; T2 = 100% PAW + foliar fertilizer; T3 = 100% PAW + foliar fertilizer + amino acids; T4 = 75% PAW; T5 = 75% PAW + foliar fertilizer; T6 = 75% PAW + foliar fertilizer + amino acids; T7 = 50% PAW; T8 = 50% PAW + foliar fertilizer; T9 = 50% PAW + foliar fertilizer + amino acids; T10 = 25% PAW; T11 = 25% PAW + foliar fertilizer; T12 = 25% PAW + foliar fertilizer + amino acids.

Discussion

Water deficit effects on potato growth and yield under greenhouse conditions

In the present greenhouse pot study, progressively lower plant-available water (PAW) levels (100% → 25%) consistently reduced vegetative growth traits (SN, SD, PL, TLN), tuber yield, and tuber carbohydrate concentrations. This response pattern is expected for potato, which is notably sensitive to water limitation during canopy development and tuber bulking, where reduced leaf expansion and assimilate supply typically translate into lower tuber biomass accumulation. In controlled environments, nutrient and water constraints can be expressed clearly because confounding field-scale variability is minimized; accordingly, several studies under greenhouse/controlled conditions have shown that suboptimal resource supply (particularly N and water) reduces chlorophyll status, biomass production, and ultimately yield ([Martins et al., 2018](#); [Chabani et al., 2024](#); [Barandalla et al., 2025](#)).

The yield results in this study also indicate that reductions in yield under increasing water deficit were accompanied by comparatively modest changes in tuber number. Such a pattern implies that yield losses were driven primarily by reduced tuber growth (i.e., smaller average tuber mass and lower biomass partitioning to tubers), rather than large reductions in tuber set. A similar inference has been reported in water-stress studies where yield preservation is more closely linked to maintaining canopy photosynthetic capacity and assimilate translocation than to increasing tuber number per se ([Horvat et al., 2010](#); [Man-Hong et al., 2020](#)).

Mitigation of drought impacts by foliar nutrition

Across PAW regimes, foliar fertilization improved growth traits and increased tuber yield relative to the non-sprayed controls, supporting the view that foliar feeding can partially compensate for stress-induced limitations in nutrient uptake and leaf physiological performance. Under drought, reduced root activity, mass flow, and nutrient diffusion commonly restrict nutrient acquisition, and foliar feeding can bypass these constraints by delivering nutrients directly to the canopy, sustaining chlorophyll content, leaf function, and carbon assimilation ([Horvat et al., 2010](#); [Man-Hong et al., 2020](#); [Wadas, 2021](#)).

[Horvat et al. \(2010\)](#), for example, reported that foliar fertilizers can maintain chlorophyll content indices and protect yield under water-stress conditions, while [Man-Hong et al. \(2020\)](#) showed that foliar-applied water-soluble humic substances improved photosynthetic characteristics and fresh tuber yield under water deficits. Similarly, exogenous foliar inputs such as ZnO and SiO₂ nanoparticles improved morphological and biochemical performance and enhanced yield and water-use efficiency under water deficit ([Al-Selwey et al., 2023](#); [Seleiman et al., 2023](#)). Together, these studies provide a strong physiological rationale for the yield gains observed here under moderate and severe PAW reduction: foliar nutrition likely supported canopy maintenance and functional leaf area, thereby sustaining assimilate availability during tuber bulking.

Additive value of amino acids when combined with foliar fertilizer

A consistent finding in this study is the additional improvement observed when amino acids were combined with foliar fertilizer (foliar fertilizer + amino acids) within each PAW level for both growth and yield. This agrees with the broader literature that foliar amino acids and amino-acid-based biostimulants frequently enhance vegetative development, nutrient status, and tuber yield and/or marketable yield in potato ([Shaheen et al., 2019](#); [Samy, 2022](#); [Kuznetsova et al., 2022](#); [Mahmoud et al., 2023](#); [Saaseea and Al-A'mry, 2024](#); [Zeebaree and Mohammed, 2025](#)).

Mechanistically, amino acids can contribute through (i) improved nutrient assimilation and translocation (acting as N-containing metabolites and chelation-like carriers), (ii) stimulation of metabolic activity and protein synthesis, and (iii) mitigation of stress via osmoprotection and antioxidant-related pathways. [Mahmoud et al. \(2023\)](#) reported that foliar application of tryptophan and its derivatives can maximize growth, yield, and tuber quality, while [Kuznetsova et al. \(2022\)](#) observed meaningful increases in marketable yield fraction following foliar application of an amino-acid-based stimulator. In a complementary context, [Henderson et al. \(2025\)](#) emphasized that individual amino acids can function as biostimulants, but responses are dose- and timing-dependent—consistent with the practical need to apply amino acids at appropriate phenological stages and concentrations.

Importantly, the additive response observed here (foliar fertilizer < foliar fertilizer + amino acids) suggests that amino acids acted as more than a simple nutrient source; they likely enhanced the efficiency of foliar-delivered nutrients by supporting assimilation and recovery under stress. This interpretation is consistent with studies where combined biostimulant strategies (e.g., salicylic acid with natural extracts or chitosan) improved growth and yield under limited irrigation via strengthened physiological resilience ([Desoky et al., 2021](#); [Morovvat et al., 2021](#)).

Interpretation of tuber carbohydrate responses under water deficit and foliar treatments

Tuber glucose, fructose, sucrose, and starch concentrations declined as PAW decreased, indicating that severe water limitation constrained carbohydrate accumulation in tubers. In potato, drought commonly restricts photosynthesis, accelerates senescence, and limits assimilate transport and storage metabolism, which can reduce starch deposition and soluble sugar pools depending on stress intensity and timing. In this study, foliar fertilizer—particularly when combined with amino acids—consistently increased soluble sugars and starch within each PAW level, suggesting partial restoration of source capacity (leaf function) and/or improved sink strength (tuber metabolic activity).

This aligns with evidence that foliar interventions under drought can sustain photosynthetic performance, improve leaf water relations, and enhance biochemical stability, leading to better carbon assimilation and allocation. [Man-Hong et al. \(2020\)](#) linked foliar humic inputs to improved photosynthesis and yield under water deficits, while [Wadas \(2021\)](#) reported that foliar-applied silicon can improve potato growth under stress conditions. Likewise, [Wang et al. \(2023\)](#) demonstrated that foliar-applied chelated calcium improved photosynthesis and tuber quality under drought, supporting the broader conclusion that foliar-applied compounds can stabilize physiological processes that govern carbohydrate formation and deposition.

A second plausible contributor is stress mitigation via antioxidant defense and reduced oxidative injury. Several foliar strategies (salicylic acid, melatonin, chitosan, and other biostimulants) have been shown to reduce ROS accumulation and lipid peroxidation while increasing enzymatic antioxidants (e.g., SOD, CAT, APX) and osmolytes, thereby preserving membrane integrity and metabolic continuity under drought ([Desoky et al., 2021](#); [El-Yazied et al., 2022](#); [Acevedo et al., 2023](#)). Although antioxidant enzymes were not measured in the present study, the improved carbohydrate status under foliar fertilizer + amino acids is consistent with stress-protection mechanisms that may sustain photosynthate production and tuber starch biosynthesis under water limitation.

Relevance of baseline nutrition and fertilization context

Because the experimental design used Hoagland solution only at planting and no further soil fertilization, foliar nutrition likely played a central role in sustaining nutrient supply during critical growth stages. The literature emphasizes that potato has high NPK demand and that insufficient fertilization reduces leaf area development and yield ([Petropoulos et al., 2020](#); [Chabani et al., 2024](#); [Abewoy, 2024](#)). In greenhouse systems, N limitation has been shown to decrease chlorophyll and biomass and reduce yield substantially ([Barandalla et al., 2025](#)). Therefore, a portion of the foliar response in this study may reflect both (i) mitigation of drought-induced nutrient uptake constraints and (ii) the broader benefit of sustaining nutrient availability during canopy formation and tuber bulking in a pot system with limited soil nutrient replenishment.

This interpretation is consistent with findings that optimized nutrient management improves physiological performance and biochemical contents ([Chabani et al., 2024](#)), while excessive fertilization may not proportionally increase yield and can increase environmental burden ([Seno Nascimento et al., 2024](#)). Moreover, different fertilizer forms (including organo-mineral strategies) can maintain yield and nutrient uptake comparably to conventional fertilizer while supporting sustainability metrics ([Oladele et al., 2025](#)). Although fertilizer form was not a variable here, these studies contextualize why foliar supplementation can be particularly influential in controlled pot experiments and under water deficit.

From an applied perspective, the consistent ranking (control < foliar fertilizer < foliar fertilizer + amino acids) across PAW levels indicates that a stage-targeted foliar program combining balanced NPK formulations with amino acids can be a practical strategy to reduce yield penalties under deficit irrigation. In agreement with prior reports, appropriate timing around early canopy development through tuber bulking appears critical for maximizing benefits ([Abd El-Hady et al., 2019](#); [Mahmoud et al., 2023](#); [Saaseea and Al-A'amry, 2024](#)). Furthermore, literature on foliar interventions under drought suggests that integrating nutrient-based sprays with stress-mitigating biostimulant concepts (e.g., silicon, salicylic acid, melatonin-like pathways) may further stabilize physiological function and water-use efficiency ([Wadas, 2021](#); [El-Yazied et al., 2022](#); [Seleiman et al., 2023](#); [Acevedo et al., 2023](#)), providing a logical avenue for future research.

This study was conducted in pots under greenhouse conditions with a single cultivar (Agria) and did not include direct physiological measurements (chlorophyll index, gas exchange, relative water content, antioxidant enzymes, osmolytes) that would allow mechanistic confirmation. Future work should (i) validate responses under field conditions and across cultivars, (ii) include physiological and biochemical stress markers to link foliar treatments to drought tolerance pathways, and (iii) examine dose-response behavior and the contribution of individual nutrient components and amino-acid profiles. Given that some biostimulant responses can be dose-sensitive ([Hu et al., 2023](#); [Henderson et al., 2025](#)) and that water deficit timing can

strongly shape tuber metabolism, factorial trials that integrate PAW level $\times$ foliar program $\times$ application timing would be particularly informative.

Finally, this study provides new evidence that a phenology-based, sequential foliar nutrition program (balanced NPK formulations supplemented with micronutrients and combined with an amino-acid product) can partially buffer the detrimental effects of progressive water deficit on potato growth, yield, and tuber carbohydrate status under greenhouse pot conditions. While numerous studies have demonstrated drought mitigation in potato using single or specialized foliar inputs such as humic substances, silicon, salicylic acid, melatonin, chitosan, or nanoparticle formulations (Man-Hong et al., 2020; Wadas, 2021; Desoky et al., 2021; El-Yazied et al., 2022; Al-Selwey et al., 2023; Seleiman et al., 2023), the present work contributes by integrating a practically deployable, fertilizer-oriented foliar schedule aligned with key developmental stages (early vegetative growth through tuber bulking). Importantly, the response pattern indicates that yield improvements were accompanied by comparatively small changes in tuber number, suggesting that foliar nutrition—especially when combined with amino acids—primarily supported tuber growth and biomass accumulation rather than substantially altering tuber set. Finally, the consistent increases in tuber soluble sugars and starch under foliar fertilizer + amino acids across PAW levels add a quality-related perspective and highlight the potential of combined foliar strategies to sustain carbon allocation and storage metabolism under water limitation.

Conclusion

Progressive reduction in plant-available water (PAW) from 100% to 25% markedly decreased potato vegetative growth (stem number, stem diameter, plant length, and total leaf number), tuber yield, and tuber carbohydrate concentrations (glucose, fructose, sucrose, and starch) under greenhouse pot conditions. Across all irrigation regimes, a stage-targeted foliar nutrition program improved growth performance and increased tuber yield relative to the non-sprayed control, demonstrating that foliar nutrient supply can partially offset the adverse effects of water deficit. The combined foliar fertilizer + amino acid treatment consistently produced the greatest improvements within each PAW level, indicating an additive benefit of amino acids when integrated with foliar nutrition. Yield responses were generally larger than changes in tuber number, suggesting that treatment effects were driven mainly by enhanced tuber growth and biomass accumulation rather than major shifts in tuber set. Overall, a sequential foliar program combining balanced NPK formulations (with micronutrients) and amino acids appears to be a practical management option to alleviate drought-related yield penalties and support tuber carbohydrate accumulation under deficit irrigation. Future research should validate these findings under field conditions, include physiological indicators of drought tolerance (e.g., gas exchange, chlorophyll status, relative water content, antioxidant activity), and optimize dose-timing combinations across cultivars and environments. From a practical standpoint, the combined foliar fertilizer + amino acid program can be prioritized particularly under moderate-to-severe water limitation (e.g., 50–25% PAW), where maintaining canopy function and tuber filling is critical for minimizing yield losses and sustaining tuber carbohydrate reserves.

Progressive reduction in plant-available water (PAW) from 100% to 25% markedly decreased potato vegetative growth (stem number, stem diameter, plant length, and total leaf number), tuber yield, and tuber carbohydrate concentrations (glucose, fructose, sucrose, and starch) under greenhouse pot conditions. Across all irrigation regimes, a stage-targeted foliar nutrition program improved growth performance and increased tuber yield relative to the non-sprayed control, demonstrating that foliar nutrient supply can partially offset the adverse effects of water deficit. The combined foliar fertilizer + amino acid treatment consistently produced the greatest improvements within each PAW level, indicating an additive benefit of amino acids when integrated with foliar nutrition. Yield responses were generally larger than changes in tuber number, suggesting that treatment effects were driven mainly by enhanced tuber growth and biomass accumulation rather than major shifts in tuber set. Overall, a sequential foliar program combining balanced NPK formulations (with micronutrients) and amino acids appears to be a practical management option to alleviate drought-related yield penalties and support tuber carbohydrate accumulation under deficit irrigation. Future research should validate these findings under field conditions, include physiological indicators of drought tolerance (e.g., gas exchange, chlorophyll status, relative water content, antioxidant activity), and optimize dose-timing combinations across cultivars and environments. From a practical standpoint, the combined foliar fertilizer + amino acid program can be prioritized particularly under moderate-to-severe water limitation (e.g., 50–25% PAW), where maintaining canopy function and tuber filling is critical for minimizing yield losses and sustaining tuber carbohydrate reserves.

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