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Impact of Water Stress Timing on Potato Yield Components: A Comparative Assessment of Two Cultivars (*Solanum tuberosum* L.) in Arid Region

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ABSTRACT

Background: Water scarcity is a principal constraint to potato production and stress timing mediates yield outcomes by affecting stage-specific processes.

Methods: Field study (2023-2024, semi-arid Algeria) using split-plot RCBD with four irrigation regimes (full irrigation vs. deficit at 45% field capacity during vegetative growth, tuber initiation, or bulking) and two cultivars (Belete and Gudenie).

Result: The largest losses occurred when stress coincided with tuber initiation and bulking; initiation stress reduced tuber number (≈37-44%), while bulking stress reduced average tuber weight (≈41-52%) and increased small, non-marketable tubers (≈28-35%), with total yield reductions up to ≈43-58% T1 (control).

Key words: Deficit irrigation, Drought tolerance, Genotype × environment interaction, Phenological sensitivity, *Solanum tuberosum*, Tuber initiation.

INTRODUCTION

Potato ranks as the world's fourth most important staple crop, delivering substantial caloric and nutritional contributions to global food security (Nasir and Toth, 2022). Its adaptability across diverse climates and exceptional yield potential per unit area have positioned it as both a subsistence staple and a lucrative cash crop for millions of smallholders and commercial producers. However, this productivity faces escalating threats from abiotic stresses, particularly water deficit, which constitutes a primary yield-limiting factor across major production regions (Nasir and Toth, 2022). Agriculture accounts for approximately 70% of global freshwater withdrawals, yet expanding urbanization, industrial demand and climate induced precipitation variability increasingly constrain irrigation availability (Djaman *et al.,* 2021). Consequently, soil moisture deficits now routinely compromise both potato yield and tuber quality, necessitating urgent development of water-efficient production systems and stress-resilient genotypes (Nasir and Toth, 2022). The sensitivity of potato to water shortages poses a substantial threat to sustainable production, making it imperative to understand crop responses to limited water availability for stabilizing yields in an era of increasing water scarcity (Nasir and Toth, 2022). Potato exhibits pronounced stage specific sensitivity to water limitation, with differential physiological impacts governed by the developmental processes occurring during stress imposition (Diaz-Valencia *et al.,* 2021). The crop life cycle spanning sprouting, vegetative development, tuber initiation, bulking and maturation displays non-uniform responses to moisture deficit (Legesse *et al.,* 2024). While early vegetative stress primarily restricts canopy expansion through reduced cell turgor and photosynthetic capacity, moderate deficits during this phase often allow partial recovery if irrigation resumes before tuberization (Legesse *et al.,* 2024). Conversely, tuber initiation represents a critically sensitive window; water deficit disrupts stolon tip differentiation by altering hormonal balances and limiting carbohydrate availability, thereby irreversibly constraining tuber set potential (Diaz-Valencia *et al.,* 2021). Once this developmental window closes, the plant has limited capacity to form new tubers, making the reduction in tuber number largely irreversible and establishing a permanent ceiling on potential yield (Diaz-Valencia *et al.,* 2021). Subsequent bulking stage stress directly impairs sink

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strength by reducing phloem assimilate transport to developing tubers, culminating in diminished average tuber weight and elevated proportions of undersized, non-marketable tubers (Mora-Sanhueza *et al.,* 2025).

Genetic variation in drought response offers substantial opportunities for mitigating yield instability across potato production systems. Morphological traits such as root system architecture, stomatal regulation dynamics and osmotic adjustment capacity differentially confer drought avoidance versus drought tolerance strategies across cultivars. While some genotypes complete life cycles rapidly to escape terminal drought, others sustain physiological function under moisture deficit through superior resource partitioning and water use efficiency. Although deficit irrigation in potato has been widely studied, rigorous evaluation of genotype × phenological-stage interactions remain limited, especially under field conditions where precise temporal control of stress is logistically challenging (Diaz-Valencia *et al.,* 2021). Most previous work has either imposed season-long water deficits or examined single-cultivar responses, without isolating how stress at vegetative growth, tuber initiation, or bulking differentially affects yield components across genotypes (Legesse *et al.,* 2024). Consequently, stage-specific trade-offs (tuber number versus tuber weight) and cultivar-specific vulnerability windows are still poorly defined. The novelty of the present study lies in combining (i) timed deficit irrigation at three distinct phenological stages under semi-arid field conditions in Algeria and (ii) a comparative assessment of two contrasting cultivars (Belete and Gudenie), thereby clarifying which growth stages and genotypes most determine yield loss and supporting more targeted irrigation and cultivar recommendations. Such research is essential for dissecting the complex interactions between stress timing and genotype, which determine the final yield outcome and inform breeding programs (Mora-Sanhueza *et al.,* 2025).

We therefore designed this research to address these gaps through targeted water withholding at distinct developmental phases in two contrasting potato cultivars. Our objectives were to: (i) quantify precise yield component responses to timed water deficits; (ii) identify differential cultivar sensitivities and adaptive mechanisms and (iii) generate evidence-based recommendations for stage specific irrigation protocols that optimize water productivity without catastrophic yield loss (Nasir and Toth, 2022 and Jama-Rodzenska *et al.,* 2021). This integrated approach combining judicious water management with superior genetics offers the most promising path toward ensuring the sustainability and productivity of potato agriculture in the face of increasing climatic uncertainty (Djaman *et al.,* 2021).

MATERIALS AND METHODS

Experimental site and climatic conditions

The field experiment was conducted during the 2023-2024 growing season (November 28, 2023 to April 2024) at El Hammadia farm. This location typifies highland potato production zones (830-850 m) experiencing intensifying water deficits, making it representative of major potato producing regions facing water availability challenges (Bourahla *et al.,* 2024). Soils were clay loams with pH 6.8, electrical conductivity 0.45 dS m^{-1}, organic matter 2.1% and total nitrogen 0.15% (Bourahla *et al.,* 2024). The 0-60 cm soil profile exhibited field capacity of 34% (v/v) and permanent wilting point of 18%, yielding total available water of ~160 mm (Bourahla *et al.,* 2024). Preceding maize cultivation and a subsequent fallow season ensured uniform soil conditions and minimized residual nutrient effects, following standard protocols for field uniformity (Bourahla *et al.,* 2024). An automated weather station located approximately 300 meters from the experimental field recorded daily maximum/minimum temperatures (24.5°C/10.2°C average), relative humidity, wind speed, sunshine hours and precipitation (Bourahla *et al.,* 2024). Total seasonal rainfall of 85 mm proved insufficient for crop requirements, necessitating supplemental irrigation to meet evapotranspirative demand (Bourahla *et al.,* 2024). Reference evapotranspiration (ETo) was calculated daily using the FAO-56 Penman-Monteith equation to guide precise irrigation scheduling and quantify crop water requirements throughout the growing season (Bourahla *et al.,* 2024).

Plant materials and experimental design

Two cultivars were selected based on documented drought response profiles: *Belete,* a nationally released variety recognized for suboptimal moisture tolerance and *Gudenie*, a commercial high yielding cultivar considered moisture sensitive (Mora-Sanhueza *et al.,* 2025).

These contrasting genotypes enabled evaluation of differential tolerance mechanisms under identical environmental conditions (Nasir and Toth, 2021). The perceived differences in drought tolerance between these varieties provided a robust framework for assessing genotype specific adaptation strategies (Nasir and Toth, 2021). A split-plot randomized complete block design with three replications was implemented to account for field heterogeneity and allow precise statistical comparison (Bourahla *et al.,* 2024). Water stress treatments occupied main plots, while cultivars were assigned to subplots (3.0 m × 3.75 m) to minimize irrigation system (Bourahla *et al.,* 2024). Each subplot comprised five rows (10 plants per row) at 75 cm inter-row and 30 cm intra-row spacing (44,444 plants ha^{-1}) (Bourahla *et al.,* 2024). The central three rows served as harvest area; outer rows and terminal plants functioned as guard plants to eliminate edge effects (Bourahla *et al.,* 2024). Buffer zones of 2 m separated blocks; 1.5 m separated main plots within blocks to prevent lateral water movement and ensure treatment integrity (Bourahla *et al.,* 2024).

Irrigation regimes and moisture management

Four irrigation treatments were imposed to isolate phenological stage specific responses:

(i) T1 (Control): Full irrigation-maintained soil moisture ≥75% field capacity throughout the season.

(ii) T2 (Vegetative stress): irrigation withheld during vegetative growth until soil moisture declined to 45% field capacity.

(iii) T3 (Initiation stress): Stress imposed during tuber initiation at 45% field capacity.

(iv) T4 (Bulking stress): Stress imposed during tuber bulking at 45% field capacity.

These thresholds align with established protocols for moderate to severe deficit irrigation that assess crop sensitivity while avoiding catastrophic plant death (Mora-Sanhueza *et al.,* 2025).

The timing of deficit irrigation at different phenological stages represents a key method for optimizing water use under scarcity while identifying critical sensitivity windows (Mora-Sanhueza *et al.,* 2025).

A drip system (2 L h^{-1} emitters, 30 cm spacing) delivered irrigation with high application uniformity and precise control over water volume delivered to each plot. Individual flow meters for each main plot accurately quantified applied volumes, enabling precise water balance calculations. Soil moisture was monitored gravimetrically and with tensiometers at 20 and 40 cm depths to ensure stress thresholds were achieved and maintained during designated periods. Irrigation volumes for T1 were calculated as ETc = ETo × Kc, using crop coefficients of 0.5 (initial), 1.15 (mid-season) and 0.75 (late-season) adjusted for local highland conditions.

Agronomic practices

The field was prepared by twice ploughing and harrowing to achieve a fine tilth suitable for uniform tuber planting and emergence. Basal fertilizers were band applied at planting: 120 kg N ha^{-1} (split: 50% at planting, 50% at 35 days after planting (DAP) hilling), 150 kg P_2O_5 ha^{-1} and 80 kg K_2O ha^{-1} (Bourahla *et al.,* 2024). This fertilization regime follows regional recommendations for high yielding potato cultivars under supplemental irrigation. Two hilling operations (35 and 60 DAP) ensured adequate soil cover for developing tubers, prevented greening and managed weeds through soil disturbance. Weeds were manually removed as needed throughout the growing season to prevent competition for water and nutrients. Protective fungicides (Mancozeb) and insecticides (Deltamethrin) were applied prophylactically against late blight and potato tuber moth per local recommendations to minimize biotic stress confounding effects.

Data collection

Five representative plants per subplot were tagged for nondestructive measurements throughout the season. Phenological development dates (50% emergence, tuber initiation and senescence onset) were recorded for each subplot when approximately 50% of plants reached respective stages. Plant height and visual canopy cover percentage were assessed at 45, 60 and 75 DAP to quantify vegetative development responses. At physiological maturity (~120 DAP, >75% foliage senescence), harvest area tubers were hand-excavated to avoid damage and ensure complete recovery. Yield components were measured according to established protocols: tuber number per plant (tubers >10 mm), average tuber weight (total fresh weight ÷ tuber number) and tuber size distribution graded into small (<30 g), medium (30-75 g) and large (>75 g) categories. Total tuber yield was recorded from net plot area and converted to t ha^{-1} for standard comparison. Water productivity was calculated as tuber yield (kg ha^{-1}) ÷ total water applied (irrigation + rainfall, m^3 ha^{-1}) to assess efficiency trade-offs between treatments.

Statistical analysis

Data were analyzed using ANOVA appropriate for split-plot designs in R v.4.2.1 to account for the hierarchical experimental structure. Normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test) assumptions were verified before analysis. The statistical model included replication, water stress treatment, cultivar and their interaction as fixed effects (Bourahla *et al.,* 2024). When F-tests indicated significant differences ($P<0.05$), means were separated using Tukey's Honestly Significant Difference (HSD) test at $\alpha = 0.05$ to control for multiple comparisons. This analytical approach follows standard procedures for agricultural field trials with factorial treatment structures.

RESULTS AND DISCUSSION

Growth and phenological responses

Water stress timing significantly impacted vegetative development parameters ($P<0.01$), confirming that early season moisture availability fundamentally establishes plant architecture. By 75 DAP, T2 (vegetative stress) reduced plant height to 48.2 cm versus 65.7 cm in T1 (control), representing a 27% reduction that persisted despite resumed irrigation. T3 and T4 stress produced intermediate heights (59.5 cm and 62.1 cm, respectively), demonstrating that post-vegetative stress has less severe effects on final stature. Gudenie exceeded Belete in height across treatments but exhibited greater relative height reduction under T2 stress, indicating its higher sensitivity to early moisture deficit. Canopy cover mirrored these patterns, with T2 stress restricting ground cover to 65% at peak development (~65 DAP) compared to >90% in T1. Furthermore, T4 stress accelerated senescence by 7-10 days, prematurely reducing photosynthetically active leaf area and shortening the effective bulking duration (Fig 1). These findings corroborate studies showing that deficit irrigation influences phenological development by altering leaf area duration and senescence timing.

Yield component modifications

Stress timing and cultivar exerted significant main and interactive effects on tuber number and average weight ($P<0.01$; Table 1), highlighting genotype-dependent responses to water deficit. Tuber number was most

severely reduced by T3 stress (initiation), decreasing by 37% in Belete (7.8 tubers plant^{-1}) and 44% in Gudenie (6.9 tubers plant^{-1}) relative to T1. This irreversible limitation on sink establishment confirms tuber initiation as the most critical period for determining yield potential. T2 stress caused moderate reductions (21-31%), whereas T4 stress did not significantly affect tuber number, as set was complete prior to stress imposition. Belete consistently outperformed Gudenie in tuber number across treatments, suggesting superior stolon development resilience. Average tuber weight was most severely impacted by T4 stress (bulking), decreasing by 41% in Belete (45.3 g) and 52% in Gudenie (41.8 g). This direct restriction of sink filling capacity demonstrates that bulking-stage moisture deficit curtails photoassimilate transport to developing tubers. Interestingly, T3 stress produced compensatory effects; with fewer tubers competing for assimilates, average weight remained higher than T4 treated plants and, for Belete, statistically equivalent to T2. This partial compensation illustrates the complex trade-offs between yield components under stress. Gudenie produced larger tubers than Belete under optimal conditions (86.5 g vs. 76.8 g) but suffered proportionally greater weight reductions under all stress treatments, confirming its specialization for high-input environments (Fig 2).

Tuber size distribution and total yield

All stress treatments significantly reduced total yield ($P<0.01$), but timing differentially affected loss magnitude and economic value. T3 and T4 produced the most severe losses: Belete declined 44% (T3) and 43% (T4); Gudenie declined 53% (T3) and 58% (T4). T2 stress caused moderate reductions of 24% (Belete) and 39% (Gudenie), highlighting the relatively lower sensitivity of vegetative stage deficit. Although T3 and T4 yields were statistically similar, their underlying mechanisms diverged T3 limited sink establishment while T4 constrained sink filling. This distinction is important for management, as irrigation restoration timing differs between scenarios. Marketability suffered dramatically under stress, particularly T4. Control treatments produced >85% large/medium tubers by weight, meeting premium market standards. T4 stress increased small tubers (<30 g) to 35% of yield in Gudenie and 28% in Belete, rendering substantial portions unsuitable for processing or fresh markets. T3 stress moderately elevated small tuber proportions but less severely than T4, as remaining tubers partially compensated during post-stress bulking. These findings emphasize that total yield alone inadequately reflects economic impact; grade distribution determines farm profitability (Table 1).

Water productivity

Water productivity was highest in T1 for both cultivars (7.1 kg m^{-3} Belete; 7.8 kg m^{-1} Gudenie), reflecting optimal yield per unit water. Stress treatments reduced WP by 32-50%, with T3 and T4 producing the lowest values (3.5-3.9 kg m^{-3}). Despite reduced water input, productivity gains were insufficient to offset yield losses, confirming that timing, rather than volume alone, determines efficiency. This trade-off between conservation and productivity

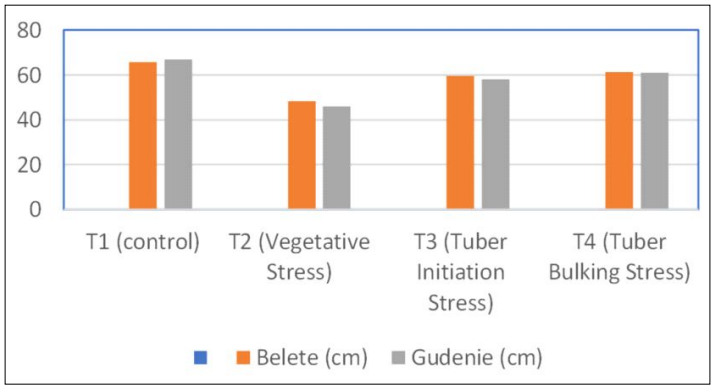


Fig 1: Plant height at 75 days after planting (DAP) for two potato cultivars under different water stress treatments.

Table 1: Tuber size distribution and total yield for two potato cultivars under different water stress treatments.

Treatment	Cultivar	Series 1	Series 2	Series 3
T1-Control	Gudenie	0.15	0.85	1.00
	Belete	0.15	0.85	0.85
T2-Veg stress	Gudenie	0.30	0.70	0.80
	Belete	0.28	0.72	0.75
T3-Init stress	Gudenie	0.39	0.61	0.70
	Belete	0.35	0.65	0.60
T4-Bulk stress	Gudenie	0.45	0.55	0.50
	Belete	0.40	0.60	0.40

underscores the need for phenology-based irrigation prioritization rather than simple deficit application (Fig 3).

Critical sensitivity windows in potato development

This study confirms that potato yield loss magnitude depends fundamentally on which developmental process is disrupted by water deficit (Diaz-Valencia *et al.,* 2021). The differential impact across phenological phases reflects distinct physiological vulnerabilities that must inform irrigation scheduling (Djaman *et al.,* 2021). Early vegetative stress reduces source capacity through stomatal limitation and impaired cell expansion, yet our data show that restored irrigation enables partial recovery before tuberization, yielding moderate yield penalties (24-39%) (Bourahla *et al.,* 2024). This aligns with literature indicating that canopy establishment, while important, does not rigidly determine final yield if stress is relieved before critical reproductive phases (Diaz-Valencia *et al.,* 2021).

Tuber initiation emerged as the most unforgiving stage for sink establishment, with the 37-44% reduction in tuber number under T3 stress corroborating reports that water deficit during this narrow window permanently compromises stolon differentiation through hormonal disruption and carbohydrate starvation (Diaz-Valencia *et al.,* 2021; Katte *et al.,* 2024). Unlike vegetative structures, tuber number cannot be compensated once the initiation period concludes, making the reduction in tuber number largely irreversible and establishing an immutable ceiling on yield potential (Diaz-Valencia *et al.,* 2021). This irreversibility underscores why irrigation must be prioritized during initiation even brief deficits inflict lasting damage that cannot be recovered through subsequent favorable conditions (Djaman *et al.,* 2021).

Bulking stage stress similarly devastated yield but through distinct mechanisms of sink limitation (Mora-Sanhueza *et al.,* 2025; Megha and Vijayalakshmi, 2024).

The 41-52% reduction in average tuber weight reflects direct restriction of assimilate flux to established sinks, as water deficit curtails phloem loading and starch deposition (Mora-Sanhueza *et al.,* 2025; Megha and Vijayalakshmi, 2024).

Our results confirm that post-initiation stress reduces net photosynthesis through stomatal closure and impairs transport efficiency, producing numerous but undersized tubers (Mora-Sanhueza *et al.,* 2025; Megha and Vijayalakshmi, 2024).

The dramatic increase in sub-30 g tubers (28-35% of yield) has profound economic implications, as processing and fresh markets demand larger tubers for profitability (Jama-Rodzenska *et al.,* 2021). This trade-off between total

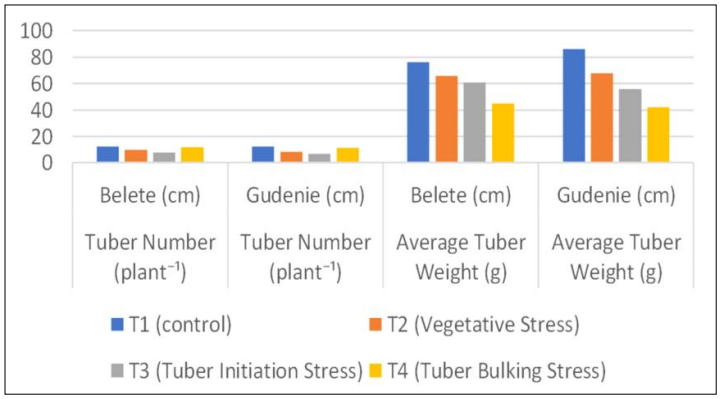


Fig 2: Interactive effects of water stress timing and cultivar on potato yield components.

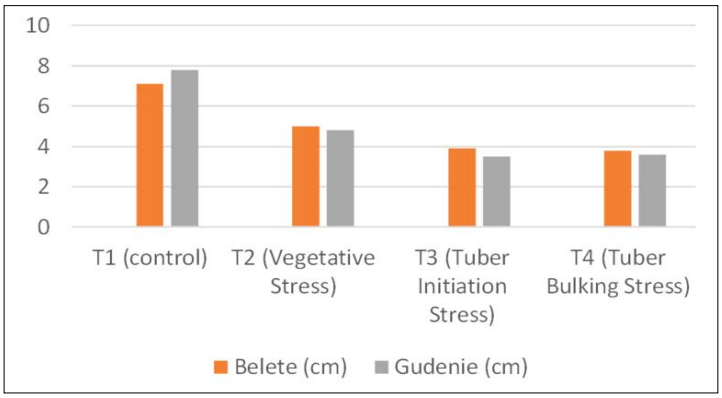


Fig 3: Water productivity (kg m^{-3}) of two potato cultivars under different water stress treatments.

biomass and marketable fraction highlights why bulking-stage water availability is equally critical as initiation-stage supply (Jama-Rodzenska *et al.,* 2021).

Genotype-dependent resilience mechanisms

The significant genotype × treatment interaction ($P<0.05$) reveals that cultivar rankings shift under stress, a phenomenon with direct breeding and management implications for water-limited environments (Nasir and Toth, 2021). Belete, though lower-yielding under optimal conditions, demonstrated superior stability across stress timings-a classic case of tolerance outperforming potential in suboptimal environments (Bourahla *et al.,* 2024). Its ability to maintain higher tuber numbers under T3 stress suggests more robust stolon development or hormonal homeostasis during differentiation, traits associated with drought avoidance strategies (Nasir and Toth, 2021). Similarly, its sustained average tuber weight under T2 and T3 stress implies efficient assimilate partitioning and possibly greater osmotic adjustment capacity, which enable physiological function maintenance under moisture deficit (Nasir and Toth, 2021; Hanumanthappa *et al.,* 2018).

Conversely, Gudenie exemplifies a high-input specialist cultivar whose performance collapses when irrigation falters (Bourahla *et al.,* 2024). Its 58% yield reduction under T4 stress, compared to 43% for Belete, highlights dependence on continuous water supply and susceptibility to sink-filling inhibition (Bourahla *et al.,* 2024). This sensitivity likely reflects less responsive stomatal regulation and inferior phloem loading efficiency under moisture deficit (Nasir and Toth, 2021). For breeding programs, these results identify Belete as a valuable donor for stress tolerance traits, particularly those governing tuber set stability and post-stress recovery, whereas Gudenie should be reserved for fully irrigated, low-risk environments (Nasir and Toth, 2021).

Yield component compensation and economic realities

Our data illustrate incomplete compensation between yield components, a critical consideration for deficit irrigation management (Nasir and Toth, 2021). When initiation-stage stress reduced tuber number, subsequent bulking under full irrigation allowed remaining tubers to enlarge, but total yield still fell 44-53% below potential (Bourahla *et al.,* 2024). This demonstrates that sink number limitation cannot be fully ameliorated by enhanced individual tuber growth, as the initial reduction in sink capacity places a rigid constraint on overall yield potential (Nasir and Toth, 2021). Conversely, bulking-stage stress offered no compensatory opportunity, as tuber number was fixed and weight reduction was uniform across the population (Bourahla *et al.,* 2024). From an economic perspective, yield quantity without quality assessment is misleading and potentially damaging to farmer livelihoods (Jama-Rodzenska *et al.,* 2021). The T4 treatment's high proportion of small tubers renders it commercially inferior to T3, despite similar total biomass, because market premiums are tied to size distribution (Jama-Rodzenska *et al.,* 2021). This underscores the necessity of grading data in water stress studies total yield masks marketability losses that drive farm profitability and food processing industry acceptance (Jama-Rodzenska *et al.,* 2021). Future deficit irrigation strategies must therefore optimize for grade distribution, not just tonnage, to ensure economic viability (Djaman *et al.,* 2021).

Implications for sustainable irrigation management

These findings provide a robust foundation for precision irrigation in water-scarce regions, where crop per drop is more relevant than maximum yield (Nasir and Toth, 2022). The principle is clear: Prioritize irrigation during initiation and bulking while accepting controlled deficits during vegetative and maturation phases, which have significantly lesser impact on final productivity (Djaman *et al.,* 2021). Regulated deficit irrigation (RDI) protocols should therefore schedule water applications based on phenological monitoring rather than fixed calendar dates, using soil moisture sensors to maintain >75% field capacity from stolon swelling through bulking (Djaman *et al.,* 2021). Adopting such targeted practices can maintain farm profitability while conserving vital water resources (Nasir and Toth, 2022).

Cultivar selection must align with water availability risk, representing a fundamental component of climate adaptation strategy (Daunde *et al.,* 2026). In regions with unreliable irrigation, Belete type cultivars offer yield stability despite lower peak potential, whereas Gudenie type cultivars maximize returns only where irrigation infrastructure is dependable (Bourahla *et al.,* 2024). This genotype-by-management matching is essential for reducing crop failure risk and optimizing resource use efficiency (Nasir and Toth, 2022). Furthermore, this research provides valuable information for potato breeding programs by identifying specific physiological trait such as robust tuberization under stress and efficient post-stress recovery that confer tolerance and should be targeted in cultivar development (Nasir and Toth, 2021).

CONCLUSION

This study shows that the timing of water stress, more than intensity alone, determines potato yield loss. Deficits during tuber initiation and bulking reduced yields by 43-58%, mainly through fewer tubers and lower tuber weight, respectively. Belete consistently outperformed Gudenie under stress, supporting genotype choice as a complementary drought-mitigation tool. In practice, irrigation should prioritise soil moisture during tuber initiation and bulking, while limited deficit irrigation may be applied at less sensitive stages. Cultivars with greater drought resilience, such as *Belete*, should be preferred where water supply is unreliable. Future work should quantify water productivity under phenology-based deficit regimes, test additional genotypes across sites and

seasons and assess the economic returns of integrated irrigation-cultivar strategies under increasing water scarcity.

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Disclaimers

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Informed consent

Not applicable (N/A). This study did not involve humans or animals.

Conflict of interest

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