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Resilience of wild and cultivated bitter melon (*Momordica charantia*) under deficit irrigation in Vietnam

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Abstract. *Nguyen TV, Kasim M, Anggraini T, Doan LN, Duong NV. 2025. Resilience of wild and cultivated bitter melon (*Momordica charantia*) under deficit irrigation in Vietnam. Biodiversitas* 26: *5248-5257*. Water scarcity increasingly constrains vegetable production in tropical regions, requiring adaptive strategies such as deficit irrigation and the use of resilient genetic resources. This study evaluated the physiological and agronomic responses of two *Momordica charantia* accessions—designated as the wild type (TCCS VP-BT08/16) and the cultivated type (TCCS VP-BT01/14)—under three irrigation regimes (80 %, 65 %, and 50 % of field capacity, FC) in a split-plot field experiment conducted during the 2024–2025 dry season in Vietnam. Growth traits, SPAD chlorophyll values, and cumulative dry fruit yield were assessed using ANOVA and Duncan's multiple range test ($P < 0.05$). Irrigation significantly influenced all measured traits ($P \leq 0.001$). The cultivated type showed strong early vigor under full irrigation but declined rapidly after ~90 days under water stress, whereas the wild type maintained stable growth, branching, leaf production, and SPAD values across irrigation levels through 120 days. Dry fruit yield was sustained at 65% FC in both accessions (~185 g plant^{-1} wild, ~178 g plant^{-1} cultivated) without significant reduction from full irrigation, while severe deficit (50% FC) caused moderate yield decline in the wild (~22%) and substantial losses in the cultivated type (~50%). These findings indicate that maintaining soil moisture at 65% FC can sustain bitter melon yield under dry-season conditions and highlight the superior drought resilience of the wild bitter melon as a valuable genetic resource for breeding climate-resilient cultivars.

Keywords: Biodiversity adaptation, deficit irrigation, *Momordica charantia*, resilience, wild and cultivated forms

INTRODUCTION

Water scarcity represents one of the most pressing challenges to sustainable agricultural production globally, particularly in tropical and subtropical regions where prolonged dry seasons and high evaporative demand threaten crop productivity (Fereres and Soriano 2007). As global freshwater resources become increasingly constrained, the development of water-efficient irrigation strategies has emerged as a critical priority for maintaining food security while preserving environmental sustainability.

Deficit Irrigation (DI)—the intentional application of water below full crop requirements—has gained widespread recognition as a promising approach to optimize Water Use Efficiency (WUE) while maintaining economically viable yields (Geerts and Raes 2009). Extensive research across cucurbitaceous crops has demonstrated that moderate reductions in irrigation can often sustain yield performance while significantly improving WUE, making DI particularly valuable in resource-limited agricultural systems (Parkash et al. 2021; Champaneri et al. 2024). A comprehensive global meta-analysis recently revealed that irrigating at approximately 35-50% of full irrigation capacity reduced yields by only 7% while increasing water productivity by 8-30% (Singh et al. 2021), underscoring the practical potential of this water management strategy.

Despite its considerable nutritional and economic importance across Asia, systematic field-based investigations of bitter melon (*Momordica charantia* L.) responses to deficit irrigation remain surprisingly limited. Most previous research has focused on combining irrigation management with soil amendments, such as biochar, to enhance growth and water productivity (Mir and Piri 2021), rather than examining irrigation effects in isolation. While bitter melon is generally characterized as moderately drought-tolerant due to its extensive rooting system and effective transpiration regulation mechanisms (Rojas-Sandoval and Acevedo-Rodríguez 2014), controlled-environment studies have revealed significant variability in drought resilience between genotypes. Notably, research has shown that wild accessions of *M. charantia* exhibit superior drought resilience compared to cultivated types, maintaining higher chlorophyll content, osmolyte accumulation, and antioxidant activity under water stress conditions (Jayaraj and Beevy 2021). However, systematic field comparisons of wild and cultivated bitter melon performance under controlled soil moisture regimes remain critically scarce.

The wild bitter melon accession (TCCS VP-BT08/16) used in this study was supplied by VAPHACO (Vietnam). Compared with the cultivated accession (TCCS VP-BT01/14), the wild accession bears smaller fruits and displays greater genetic diversity (Pham et al. 2019). It was selected for evaluation because wild bitter melon has been reported to maintain relative water content, chlorophyll stability, and antioxidant activity under drought stress (Jayaraj and Beevy 2021), traits consistent with delayed senescence and canopy persistence. Such stress-adaptive features make it a promising donor for breeding programs aiming at yield stability and resilience under water deficit.

This knowledge gap extends beyond immediate agronomic concerns to encompass broader implications for biodiversity conservation and genetic resource management in agricultural systems. The domestication process has progressively narrowed the genetic base of cultivated bitter melon, thereby reducing its adaptive potential under environmental stress conditions (Cui et al. 2020). In contrast, wild accessions retain substantial morphological and molecular diversity that represents an invaluable reservoir of adaptive traits (Alhariri et al. 2021). Wild Crop Relatives (CWRs) are increasingly recognized as essential genetic repositories for tolerance mechanisms to drought, salinity, and temperature extremes (Kapazoglou et al. 2023). Recent scientific advances have highlighted not only their intrinsic genetic value but also their associated microbiomes—often termed the "second plant genome"—which fundamentally underpin plant resilience and ecosystem recovery under environmental stress (Waqas et al. 2025). Nevertheless, conservation efforts and integration of CWRs into formal breeding programs remain inadequate, despite their widely acknowledged importance for maintaining agrobiodiversity, enhancing climate adaptation capacity, and ensuring global food security (Ortiz et al. 2024).

To address these critical research gaps, a comprehensive field experiment was conducted during the 2024–2025 dry season in Vietnam to systematically evaluate the physiological and agronomic resilience of wild and cultivated bitter melon genotypes under three distinct deficit irrigation regimes. We hypothesized that (i) moderate deficit irrigation (65% field capacity, FC) would sustain dry fruit yield relative to full irrigation treatments, and (ii) the wild genotype would demonstrate superior physiological resilience and growth stability compared to the cultivated type under water-limited conditions. By integrating agronomic performance assessment with biodiversity conservation principles, this study aims to establish practical water-saving irrigation thresholds while simultaneously highlighting the ecological and genetic value of wild bitter melon germplasm for developing more resilient and sustainable agroecosystems.

MATERIALS AND METHODS

Experimental site and season

The field experiment was conducted at Kien Giang University, Chau Thanh District, Kien Giang Province, Vietnam (9°9′14″ N, 105°14′25″ E) during the 2024-2025 dry season. The experiment was conducted on sandy loam soil (62% sand, 30% silt, and 8% clay) with a pH of 6.5 ± 0.06, Electrical Conductivity (EC) of 181.61 $\mu S\ cm^{-1}$, and Field Capacity (FC) of 34.66 ± 1.84%. The ambient air temperature and relative humidity during the experimental period were 28.8 ± 0.64°C and 71.08 ± 1.23%, respectively. A split-plot design with three replications was used. The main-plot factor was bitter melon (*M. charantia*) cultivar: wild bitter melon (TCCS VP-BT08/16) and cultivated bitter melon (TCCS VP-BT01/14). The subplot factor was soil moisture level maintained at 0.80, 0.65, and 0.50 of field capacity (FC) (i.e., $\theta/\theta\_FC = 0.80; 0.65; 0.50$). In total, 18 plots (2 cultivars × 3 moisture levels × 3 replications) were established, each measuring 30 m^2 (3 m × 10 m).

Plants were spaced at 100 × 100 cm. Each plot consisted of two rows with a total of 20 plants, of which 10 central plants were tagged and used for growth and yield measurements. Plots were separated by 0.5 m alleys, while replicates were spaced 3 m apart with 1 m row spacing between blocks to minimize border effects. Treatments within each replicate were randomly assigned.

Experimental design and treatments

Fertilizer was applied according to local recommendations for bitter melon cultivation on sandy loam soil, following Palada and Chang (2003). The total nutrient supply was 184 kg N, 112 kg P_2O_5, and 124 kg K_2O per hectare. Well-decomposed farmyard manure was incorporated as a basal organic fertilizer before transplanting. A basal dose of 36 kg N, 54 kg P_2O_5, and 36 kg K_2O ha^{-1} was applied as chemical fertilizer prior to planting, placed approximately 10 cm away from the plant rows. Top-dressing was then applied four times: the first at the 4-6 leaf stage, and subsequently at two-week intervals. Each top-dressing provided 30 kg N, 7.5 kg P_2O_5, and 15 kg K_2O ha^{-1}. This schedule ensured a steady nutrient supply throughout the crop cycle.

Irrigation management

Soil moisture was regulated through an automatic drip irrigation system using sensors (DKAD03, Loc Phat Co., Vietnam) installed at 15-20 cm depth in each plot. Sensors were calibrated at the beginning of the season against gravimetric soil moisture samples, and target levels were maintained at 80%, 65%, and 50% of Field Capacity (FC). To ensure accuracy, sensor readings were cross-checked every 10 days with a handheld soil moisture tester (DM-15, Takemura, Japan). Deviations greater than ± 3% FC were considered unacceptable, and irrigation schedules were adjusted accordingly.

Although actual irrigation volumes were not recorded, soil moisture dynamics were monitored throughout the season. Figures 1 and 2 illustrate that soil water content was consistently differentiated and maintained among the three irrigation regimes: from 10 to 120 days after transplanting (DAT) in wild bitter melon and from 10 to 90 DAT in cultivated bitter melon, after which the latter senesced. These records confirm that the intended FC levels were effectively sustained during the experiment.

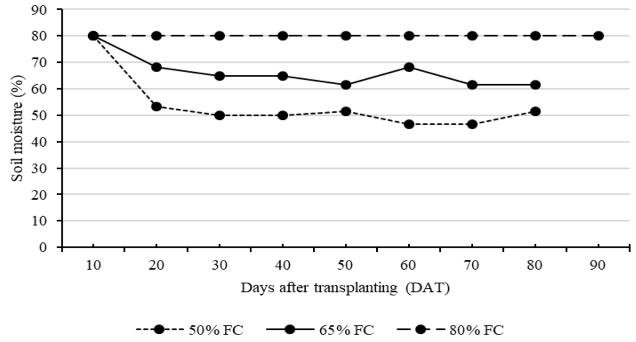

Figure 1. Soil moisture dynamics of cultivated bitter melon under three irrigation regimes (80%, 65%, and 50% of field capacity) from 10 to 90 days after transplanting

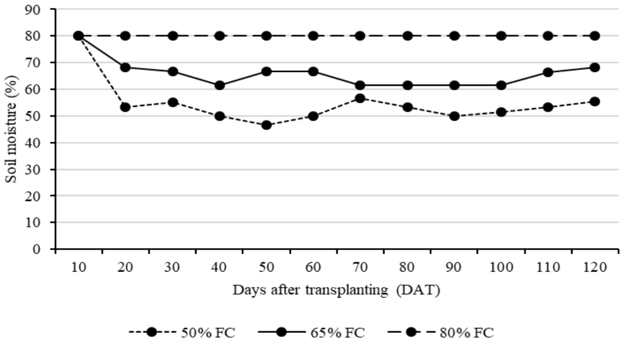

Figure 2. Soil moisture dynamics of wild bitter melon under three irrigation regimes (80%, 65%, and 50% of field capacity) from 10 to 120 days after transplanting

Plant materials and crop management

Seeds of both wild and cultivated bitter melon were supplied by Van Phat Company (VAPHACO, Vietnam). Seedlings were transplanted on 4 December 2024. To ensure uniform crop management, all plots were mulched with a black polyethylene sheet to suppress weeds and reduce soil evaporation. As a basal organic amendment, well-decomposed rice straw manure was incorporated into the soil prior to transplanting. Plants were supported using a triangular trellis system combined with a 20-cm mesh climbing net, which facilitated vertical growth, improved light penetration, and allowed convenient harvesting.

Sampling scheme and measurements

In each subplot, ten plants were randomly tagged and used for repeated measurements at 10-day intervals from 10 to 120 days after transplanting (DAT). The following traits were recorded following standard protocols:

Plant height (cm): measured from the soil surface to the shoot apex using a measuring tape. Stem diameter (mm): measured 5 cm above the soil surface using a digital caliper. Number of primary branches and total leaves (plant^{-1}): manually counted on tagged plants. SPAD value: measured using a chlorophyll meter (SPAD-502Plus, Konica Minolta, Japan) on the 3rd-5th fully expanded leaf.

Dry fruit yield (g plant^{-1}): all marketable fruits were harvested at commercial maturity. Subsamples were oven-dried to constant weight at 70°C to determine dry matter content, and cumulative dry fruit yield per plant was calculated as fresh weight × dry matter %.

Statistical analysis

Data were analyzed under a split-plot framework. For traits measured repeatedly (plant height, stem diameter, branching, leaf number, SPAD), plot means were subjected to split-plot ANOVA separately by sampling date, with the appropriate main-plot error term. Dry fruit yield was analyzed at the plot level. Data distribution and variance homogeneity were checked using the Shapiro–Wilk and Levene's tests; logarithmic or square-root transformations were applied when assumptions were not met. Post-hoc comparisons among irrigation levels were performed with Duncan's multiple range test at $\alpha = 0.05$ (two-sided). Analyses were conducted using SPSS v20.

RESULTS AND DISCUSSION

Plant height under FC-based irrigation and genotype effects

Based on the ANOVA results for bitter melon plant height under deficit irrigation (Table 1), Field Capacity (FC) treatments showed highly significant effects during early growth stages (30 and 60 DAT, $P < 0.001$) but became non-significant at later stages. Variety effects were significant only at 60 DAT ($P<0.001$), while the FC × Variety interaction was highly significant at 30 and 60 DAT ($P < 0.001$), indicating that wild and cultivated bitter melon varieties respond differently to water stress conditions. The diminishing treatment effects in later growth stages (90-120 DAT) likely reflect plant senescence and adaptation to stress conditions, with the most critical period for irrigation management occurring during the first 60 days after transplanting.

Plant height was significantly affected by irrigation regime and genotype (Figure 3). At 60 DAT, the cultivated type under 80% FC reached nearly 194 cm, significantly taller than the wild type. However, by 90 DAT, cultivated plants subjected to deficit irrigation had senesced, while the wild genotype maintained stable height across all irrigation levels through 120 DAT. Moderate deficit (65% FC) sustained stem elongation in the wild type without yield penalty, whereas severe deficit (50% FC) significantly reduced plant height.

The contrasting responses between wild and cultivated bitter melon highlight the adaptive advantage of wild genotypes under water-limited conditions. The early vigor of the cultivated type under full irrigation is consistent with domestication-driven selection for rapid growth and high productivity. However, its early senescence under deficit irrigation underscores the reduced plasticity associated with a narrow genetic base (Cui et al. 2020). By contrast, the wild genotype exhibited sustained stem elongation under moderate deficit and maintained structural integrity even at 50% FC (Figure 3), confirming its superior drought resilience.

Table 1. ANOVA for plant height (cm)

Source	30DAT	60 DAT	90 DAT	120 DAT
	Df/ f,/Sig.			
Corrected model	11/8.824/.000	11/42.297/.000	9/1.667/.106	8/2.275/.030
Intercept	1/26288.011/.000	1/171634.993/.000	1/105662.5002/.000	1/112868.974/.000
Rep	2/.922/.400	2/.896/.410	2/1.427/.244	2/.529/.591
FC	2/35.481/.000	2/120.261/.000	2/2.595/.079	2/1.769/.177
Variety	1/.057/.812	1/77.441/.000	1/2.955/.088	N/A
REP * FC	4/1.425/228	4/.402/.807	4/.881/.478	4/3.402/.013
FC * variety	2/9.252/.000	2/71.949/.000	N/A	N/A
Error	168	168	110	81
Total	180	180	120	90
Corrected total	179	179	119	89

Note: DAT: Days after transplanting, N/A: Missing data due to plant senescence of cultivated bitter melon variety (from 90 to 120 DAT); Df: Degree of freedom, sig.: Significant

Table 2. ANOVA for stem diameter (mm)

Source	30 DAT	60 DAT	90 DAT	120 DAT
	Df/ f,/Sig.			
Corrected model	11/30.057/.000	11/63.050/.000	9/50.953/.000	8/29.531/.000
Intercept	1/14446473/.000	1/95016.642/.000	1/144299.938/.000	1/70457.834/.000
Rep	2/2.472/.087	2/3.875/.023	2/2.062/.132	2/2.923/.059
FC	2/14.521/.000	2/318.189/.000	2/219.678/.000	2/108.953/.000
Variety	1/269.941/.000	1/27.412/.000	1/31.886/.000	N/A
REP * FC	4/4.116/.003	4/1.562/.187	4/4.371/.003	4/3.125/.019
FC * variety	2/5.118/.007	2/7.879/.001	N/A	N/A
Error	168	168	110	81
Total	180	180	120	90
Corrected total	179	179	119	89

Note: DAT: Days after transplanting; N/A: Missing data due to plant senescence of cultivated bitter melon variety (from 90 to 120 DAT); Df: Degree of freedom, sig.: Significant

These findings align with previous reports in cucurbits, where moderate regulated deficit irrigation preserved plant height while severe stress suppressed vegetative growth (Jayaraj and Beevy 2021; Kafle et al. 2025). The persistence of the wild genotype suggests stronger osmotic adjustment and vascular development, traits commonly retained in crop wild relatives (Kapazoglou et al. 2023). Beyond agronomic implications, these results highlight the genetic and ecological value of wild bitter melon. Its adaptive traits support biodiversity-based adaptation and breeding for climate-resilient agriculture (Ortiz et al. 2024; Waqas et al. 2025).

Stem diameter: thickening dynamics and drought resilience

Table 2 reveals that Field Capacity (FC) treatments showed highly significant effects throughout the entire growing season (30-120 DAT, $P < 0.001$), indicating consistent water stress impacts on stem development. Variety effects were highly significant at 30, 60, and 90 DAT ($P < 0.001$), with wild varieties generally exhibiting larger stem diameters than cultivated types. The FC × Variety interaction was significant during early growth (30 and 60 DAT, $P < 0.01$), demonstrating differential responses between varieties to water stress. Unlike plant height, stem diameter maintained strong treatment sensitivity throughout the growth period, making it a reliable indicator for water stress assessment in bitter melon.

Stem diameter increased steadily with plant age and was significantly affected by irrigation level and genotype (Figure 4). The cultivated type achieved early thickening, peaking at ~6.8 mm by 60 DAT under 80% FC, but growth stagnated and plants senesced before 100 DAT. In contrast, the wild type continued thickening through 120 DAT, reaching up to 10.6 mm under 80% FC, and maintained higher diameters even under deficit irrigation (9.4 mm at 50% FC).

The results reveal clear differences between wild and cultivated bitter melon in stem thickening under water deficit. The cultivated type benefited from rapid early girth expansion under full irrigation but failed to sustain vascular development under stress, reflecting vulnerability to drought-induced senescence. By contrast, the wild type sustained stem growth under 65% FC and maintained thickening even at 50% FC, showing strong drought tolerance.

Comparable results have been reported in cucurbits: drought-tolerant genotypes maintain vascular growth through osmotic adjustment and lignification, whereas sensitive genotypes show stagnation and collapse under stress (Jayaraj and Beevy 2021; Kaman et al. 2023). These findings support the hypothesis that wild bitter melon retains functional traits that prolong vegetative survival under deficit irrigation. Beyond agronomy, this resilience underscores the biodiversity value of wild germplasm as a gene pool for breeding climate-resilient cucurbit crops (Ortiz et al. 2024; Waqas et al. 2025).

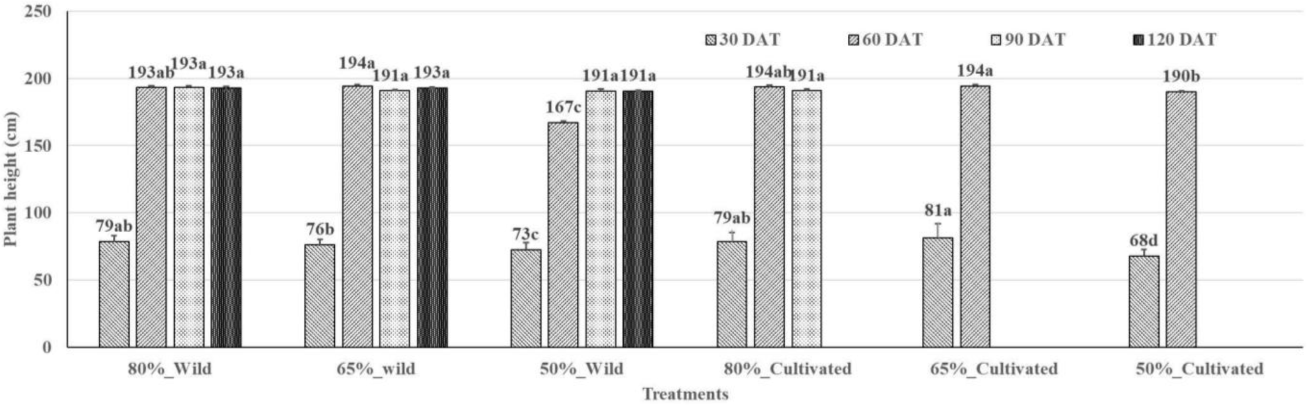

Figure 3. Plant height of wild and cultivated bitter melon under deficit irrigation at different soil moisture levels (mean ± SE). DAT: Day after transplanting; missing data due to plant senescence of cultivated bitter melon variety (from 90 to 120 DAT), different letters within DAT indicate significant differences (P ≤ 0.05), Duncan's test

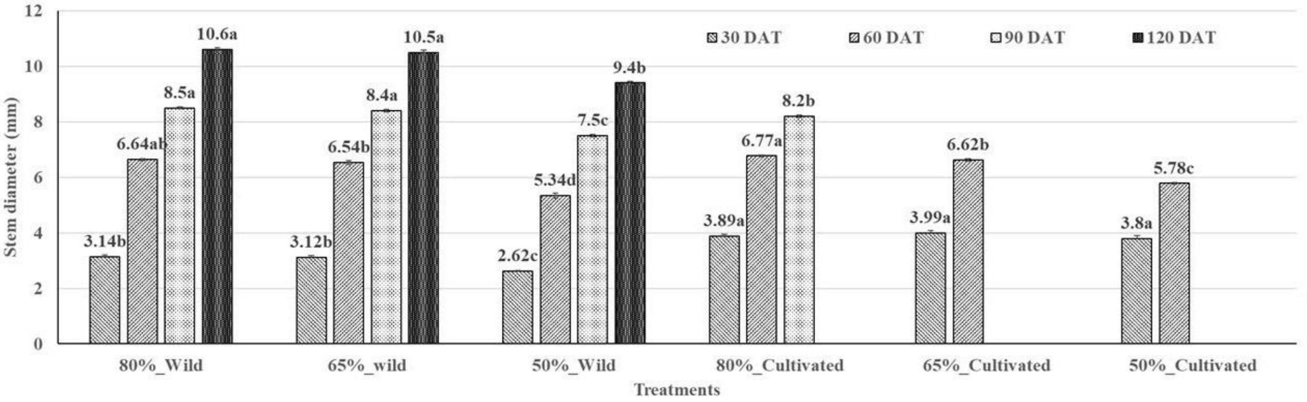

Figure 4. Stem diameter of wild and cultivated bitter melon as influenced by soil moisture regimes (mean ± SE). DAT: Day after transplanting; missing data due to plant senescence of cultivated bitter melon variety (from 90 to 120 DAT), different letters within DAT indicate significant differences (P ≤ 0.05), Duncan's test

Primary branching: canopy structuring under water deficit

Based on Table 3, the ANOVA results demonstrate highly significant effects of the corrected model on the number of primary branches across all measurement periods (30, 60, 90, and 120 DAT, all $P < 0.001$). Fertilizer Concentration (FC) was the most dominant factor, showing highly significant effects at all time points ($P < 0.001$), while variety effects were significant through 90 DAT but became non-significant by 120 DAT. The interaction between replication and fertilizer concentration (REP × FC) was significant at 30, 60, and 120 DAT, and the FC × Variety interaction was significant at 30 and 60 DAT but disappeared at later stages. Replication effects were generally non-significant except at 120 DAT, indicating consistent experimental conditions. The decreasing sample sizes from 180 plants at early stages to 90 plants at 120 DAT reflect natural plant senescence during the experimental period.

Primary branching was significantly influenced by genotype and irrigation regime (Figure 5). The wild genotype developed more branches than the cultivated type at all irrigation levels and maintained branch numbers through 120 DAT. At 60 DAT, wild plants under 80% FC reached ~34 branches per plant compared with ~25 in the cultivated type. Branch number in the wild genotype stabilized after 60 DAT and remained constant under both full and deficit irrigation. In contrast, the cultivated type senesced early: at 80% FC, plants survived until 90 DAT, while at 65% and 50% FC, plants senesced after 60 DAT.

The sustained branching capacity of the wild genotype under both full and deficit irrigation demonstrates greater morphological resilience and adaptability. By contrast, the cultivated type exhibited reduced branching and early senescence under stress, particularly at 65% and 50% FC, highlighting its limited plasticity. These findings are consistent with earlier reports that drought-tolerant cucurbit genotypes maintain branching and canopy stability, whereas sensitive types experience reduced lateral development and premature collapse (Jayaraj and Beevy 2021; Khan et al. 2024).

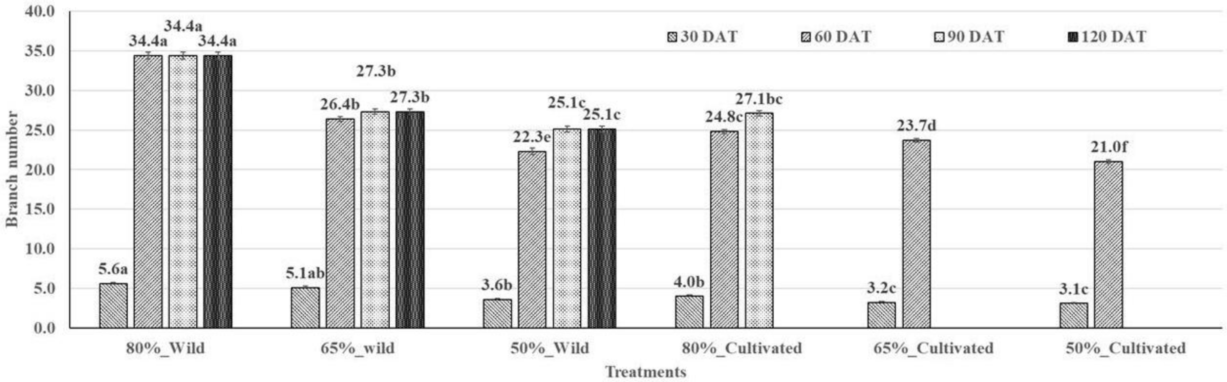

Figure 5. Number of primary branches per plant in wild and cultivated bitter melon under deficit irrigation (mean ± SE). DAT: Day after transplanting; missing data due to plant senescence of cultivated bitter melon variety (from 90 to 120 DAT), different letters within DAT indicate significant differences (P ≤ 0.05), Duncan's test

Table 3. ANOVA Number of primary branches (no. plant^{-1})

Source	30DAT	60 DAT	90 DAT	120 DAT
	Df/ f,/Sig.			
Corrected model	11/26.480/.000	11/108.658/.000	9/51.513/.000	8/56.496/.000
Intercept	1/4960.447/.000	1/40012.208/.000	1/18464.813/.000	1/20500.043/.000
Rep	2/1.215/.299	2/.368/.693	2/.798/.453	2/3.379/.039
FC	2/53.269/.000	2/329.078/.000	2/199.515/.000	2/212.979/.000
Variety	1/142.694/.000	1/314.423/.000	1/302.787/.000	N/A
REP * FC	4/2.858/.025	4/4.671/.001	4/1.906/.114	4/4.812/.002
FC * variety	2/14.091/.000	2/101.621/.000	N/A	N/A
Error	168	168	110	81
Total	180	180	120	90
Corrected total	179	179	190	89

Note: DAT: Days after transplanting, N/A: Missing data due to plant senescence of cultivated bitter melon variety (from 90 to 120 DAT), Df: Degree of freedom, sig.: Significant

Table 4. ANOVA for SPAD

Source	30 DAT	60 DAT	90 DAT	120 DAT
	Df/ f,/Sig.			
Corrected model	11/6.978/.000	11/5.442/.000	9/57.392/.000	8/4.230/.000
Intercept	1/38393.026/.000	1/121250.879/.000	1/39776.700/.000	1/75795.325/.000
Rep	2/.284/.753	2/3.335/.038	2/1.012/.367	2/1.691/.191
FC	2/14.226/.000	2/9.953/.000	2/2.359/.099	2/.130/.879
Variety	1/25.977/.000	1/.024/.877	1/368.834/.000	N/A
REP * FC	4/3.238/.014	4/2.032/.092	4/2.048/.093	4/7.550/.000
FC * variety	2/4.402/0.14	2/12.567/.000	N/A	N/A
Error	168	168	110	81
Total	180	180	120	90
Corrected total	179	179	119	89

Note: DAT: Days after transplanting, N/A: Missing data due to plant senescence of cultivated bitter melon variety (from 90 to 120 DAT), Df: Degree of freedom, sig.: Significant

The wild form preserved canopy structure under deficit irrigation, reflecting robust physiology and morphology that supported survival under prolonged stress. Beyond agronomic significance, this resilience underscores the ecological and genetic value of wild germplasm as a reservoir of adaptive traits for breeding stress-resilient cucurbits (Ortiz et al. 2024; Waqas et al. 2025).

SPAD chlorophyll index: photosynthetic stability under deficit

Based on Table 4 ANOVA results for SPAD chlorophyll index in bitter melon (*M. charantia* L.), the corrected model showed high significance (P < 0.001) across all sampling periods (30, 60, 90, and 120 days after transplanting), indicating substantial treatment effects on chlorophyll content. Field capacity (FC) irrigation levels demonstrated significant effects at 30 DAT and 60 DAT (P

< 0.001), but became non-significant at later growth stages (90 and 120 DAT), suggesting that irrigation stress impacts are most pronounced during early vegetative development. Variety effects were highly significant at 30 DAT and 90 DAT ($P < 0.001$), indicating genotype-dependent responses to water stress that vary temporally. The significant interaction between replication and field capacity (REP × FC) at 30 DAT ($P = 0.014$) and 120 DAT ($P < 0.001$), along with the FC × Variety interaction at 60 DAT ($P < 0.001$), reveals complex environmental and genetic interactions affecting chlorophyll synthesis under varying irrigation regimes, with wild and cultivated varieties responding differentially to water stress throughout the growing season.

SPAD chlorophyll index was significantly influenced by genotype and irrigation level (Figure 6). At 30 DAT, the cultivated genotype under 80% FC showed slightly higher SPAD values (~37) than the wild type (~36). However, from 60 DAT onwards, the wild genotype maintained stable or even increasing SPAD values across irrigation regimes, ranging from 37 to 39 until 120 DAT. By contrast, the cultivated type experienced a sharp decline in SPAD values after 80 DAT, particularly under 80% FC, where values dropped to ~29 at 90 DAT, before senescence prevented further measurements at 120 DAT.

The contrasting SPAD dynamics between wild and cultivated bitter melon emphasize the superior physiological resilience of the wild genotype under deficit irrigation. While the cultivated type exhibited high early chlorophyll content under full irrigation, its decline after 80 DAT indicates accelerated senescence and loss of photosynthetic activity under stress. The wild genotype, in contrast, sustained high chlorophyll content under both moderate and severe deficit, suggesting efficient leaf retention and stress adaptation mechanisms.

These findings align with previous reports that drought-tolerant cucurbit genotypes maintain chlorophyll stability, reflecting delayed senescence and stronger antioxidant defense (Jayaraj and Beevy 2021; Champaneri et al. 2024). The wild genotype preserved photosynthetic integrity under deficit irrigation, making it a valuable resource for breeding stress-resilient cultivars. From a biodiversity perspective, such traits reinforce the ecological importance of conserving wild bitter melon as a genetic reservoir for climate-resilient agriculture (Kapazoglou et al. 2023; Ortiz et al. 2024; Waqas et al. 2025).

Total leaf number: canopy persistence across moisture levels

Significant differences ($P \leq 0.05$) were observed across multiple factors and time periods in bitter melon cultivation. The corrected model showed high significance ($P < 0.001$) at all measurement periods (30, 60, 90, and 120 DAT), indicating substantial treatment effects on leaf development (Table 5). Field Capacity (FC) consistently demonstrated highly significant effects ($P < 0.001$) throughout the growth period, suggesting that irrigation regimes critically influenced leaf production. Variety effects were highly significant ($P < 0.001$) from 30 to 90 DAT, with cultivated varieties generally outperforming wild types, though this effect diminished by 120 DAT due to plant senescence. The FC × Variety interaction was significant at early growth stages (30 and 60 DAT, $P < 0.001$), indicating differential responses of wild and cultivated varieties to irrigation treatments. Replication effects were only significant at 90 DAT ($P < 0.001$), while REP × FC interactions showed significance at 60 and 90 DAT ($P < 0.001$), suggesting some spatial variability in treatment responses during mid-growth periods.

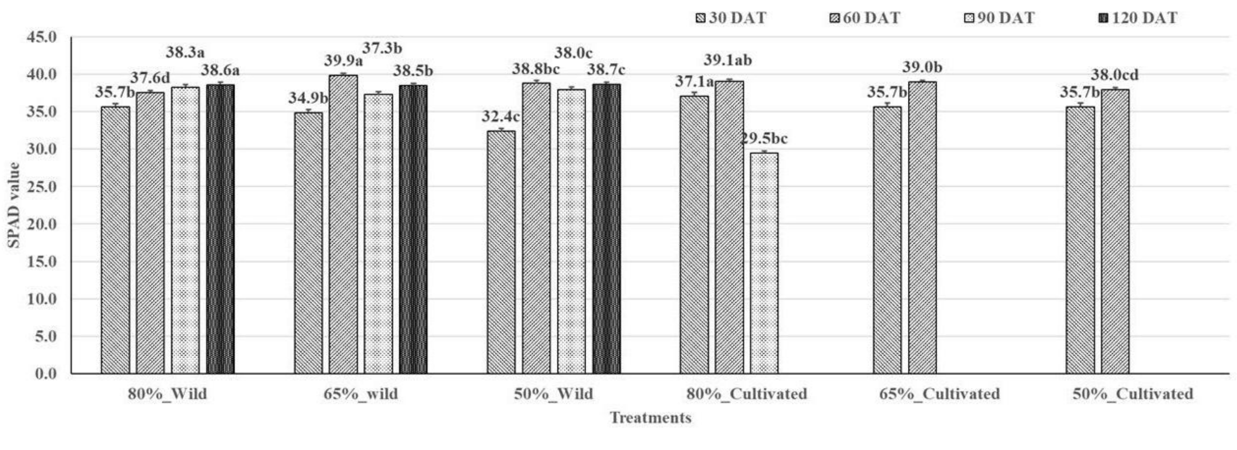

Figure 6. SPAD chlorophyll index of wild and cultivated bitter melon across irrigation levels (mean ± SE). DAT: Day after transplanting; missing data due to plant senescence of cultivated bitter melon variety (from 90 to 120 DAT), different letters within DAT indicate significant differences ($P \leq 0.05$), Duncan's test

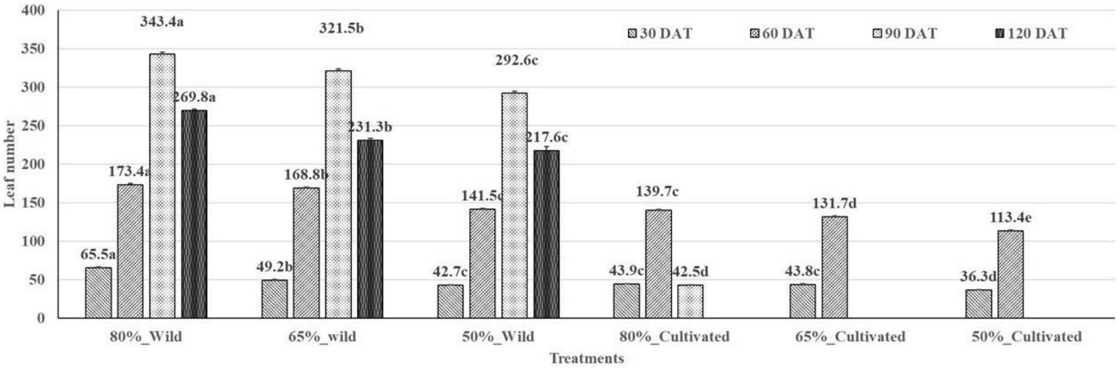

Figure 7. Total leaf number of wild and cultivated bitter melon under full and deficit irrigation conditions (mean ± SE). DAT: Day after transplanting; missing data due to plant senescence of cultivated bitter melon variety (from 90 to 120 DAT), different letters within DAT indicate significant differences (P ≤ 0.05, Duncan's test

Table 5. ANOVA for leaf number (plant^{-1})

Source	30 DAT	60 DAT	90 DAT	120 DAT
	Df/ f,/Sig.			
Corrected model	11/101.471/.000	11/183.520/.000	9/2590.429/.000	8/18.961/.000
Intercept	1/29195.710/.000	1/96774.162/.000	1/62256.494/.000	1/16882.030/.000
Rep	2/1.438/.240	2/2.372/.096	2/15.030/.000	2/.465/.630
FC	2/255.734/.000	2/360.617/.000	2/256.929/.000	2/71.785/.000
Variety	1/410.748/.000	1/1253.775/.000	1/17941.387/.000	N/A
REP * FC	4/2.025/.093	4/5.810/.000	4/6.505/.000	4/1.798/.137
FC * variety	2/91.493/.000	2/7.867/.001	N/A	N/A
Error	168	168	110	81
Total	180	180	120	90
Corrected total	179	179	119	89

Note: DAT: Days after transplanting; N/A: Missing data due to plant senescence of cultivated bitter melon variety (from 90 to 120 DAT); Df: Degree of freedom, sig.: Significant

Leaf production was strongly influenced by genotype and irrigation level (Figure 7). The wild genotype produced substantially more leaves than the cultivated type across irrigation regimes. At 60 DAT, wild plants under 80% FC had ~173 leaves per plant compared with ~140 in the cultivated type. Leaf numbers in the wild genotype peaked around 90 DAT and remained high until 120 DAT, even under 50% FC. In contrast, leaf production in the cultivated type declined rapidly after 80 DAT, with severe reductions by 90 DAT and no surviving plants at 120 DAT under deficit irrigation.

The greater leaf production of the wild genotype reflects its superior capacity to maintain canopy development and photosynthetic surface area under deficit irrigation. By contrast, the cultivated type exhibited limited leaf expansion and premature leaf loss, consistent with its earlier senescence under water deficit. These differences highlight the contrasting adaptive strategies: the wild genotype maintains canopy integrity under moderate and severe deficit, while the cultivated type sacrifices leaf area under stress.

Comparable observations have been reported in cucurbits, where drought-tolerant genotypes sustain higher leaf area and delayed senescence, ensuring continued carbon assimilation and yield stability (Jayaraj and Beevy 2021; Champaneri et al. 2024). The wild-form maintained leaf production under deficit irrigation, underscoring its ecological value. These traits can be introgressed into cultivated germplasm to enhance stress tolerance and biodiversity adaptation (Kapazoglou et al. 2023; Ortiz et al. 2024; Waqas et al. 2025).

Dry fruit yield and the water-saving threshold (0.65 FC)

Based on Table 6 ANOVA results for dry fruit yield, the corrected model was marginally significant (P = 0.037), indicating overall treatment effects on bitter melon fruit production. Field capacity (FC) was the only factor showing high statistical significance (P = 0.002), demonstrating that irrigation regimes were the primary determinant of dry fruit yield in bitter melon cultivation. This finding suggests that water management strategies significantly influence fruit productivity, with optimal irrigation levels being critical for maximizing yield performance in both wild and cultivated bitter melon varieties.

Seasonal cumulative dry fruit yield was significantly affected by irrigation regime but not by genotype or their interaction (Figure 8). At 65% FC, yield was maintained in both wild and cultivated genotypes (~185 g plant^{-1} and ~178 g plant^{-1}, respectively), not significantly different from full irrigation (80% FC). At 50% FC, however, yields declined markedly, especially in the cultivated type (~88 g plant^{-1}, ~50% reduction), whereas the wild type showed a more moderate decrease (~138 g plant^{-1}, ~22% reduction).

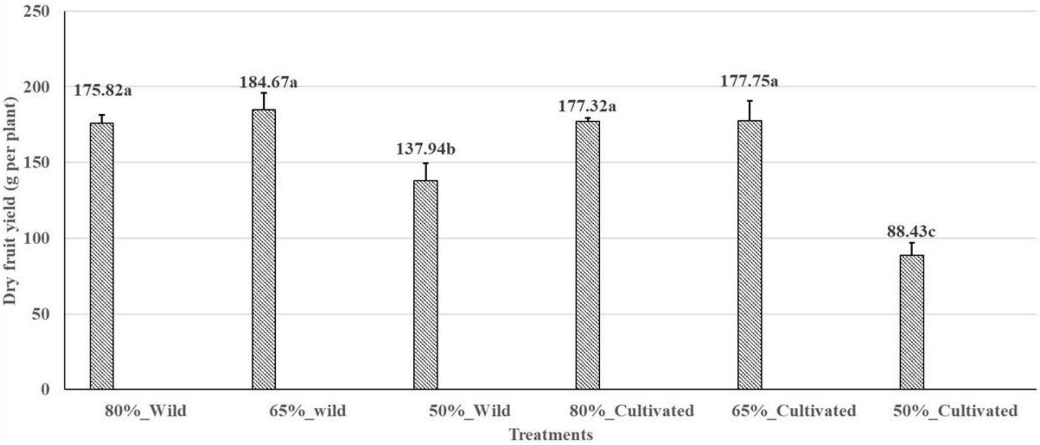

Figure 8. Seasonal cumulative dry fruit yield of wild and cultivated bitter melon under three irrigation regimes (mean ± SE). DAT: Day after transplanting; missing data due to plant senescence; different letters within DAT indicate significant differences (P ≤ 0.05), Duncan's test

Table 6. ANOVA for dry fruit yield (g plant^{-1})

Source	Dry fruit yield
	DF/f/sig
Corrected model	11/4.600/.037
Intercept	1/1034.885/.000
Rep	2/.021/.979
FC	2/20.217/.002
Variety	1/3.520/.110
REP * FC	4/.341/.842
FC * variety	2/2.618/.152
Error	6
Total	18
Corrected total	17

Note: Df: Degree of freedom, sig.: Significant

The research findings demonstrate that moderate deficit irrigation (65% FC) effectively maintains dry fruit yield in both wild and cultivated bitter melon genotypes, consistent with studies showing that "regulated deficit irrigation can maintain yield while improving water productivity" (Geerts and Raes 2009; Champaneri et al. 2024). At this threshold, both genotypes sustained comparable yields (~185 g plant^{-1} for wild and ~178 g plant^{-1} for cultivated) without significant reduction from full irrigation treatments, establishing this level as "economically viable for water-saving production systems" (Khan et al. 2024). However, under severe water stress (50% FC), yield stability diverged markedly between genotypes, with "wild bitter melon experiencing only 22% yield reduction compared to 50% decline in cultivated varieties" (Abdelraouf et al. 2020). This superior drought resilience in wild genotypes reflects "improved osmotic adjustment capacity and more efficient water utilization strategies" along with enhanced root system architecture commonly found in wild accessions (Kou et al. 2022). These differential responses align with global trends showing that "moderate water stress (30-40% reduction from full irrigation) can maintain 85-95% of potential yield while improving water use efficiency by 15-25% in cucurbitaceous crops" (Singh et al. 2021; Khan et al. 2024). The study underscores "the critical importance of incorporating wild germplasm into breeding programs for developing climate-resilient bitter melon cultivars" capable of sustaining productivity under increasingly variable precipitation patterns in the context of climate change adaptation.

Although the wild genotype (TCCS VP-BT08/16) demonstrated superior drought resilience in terms of growth and yield maintenance, its commercial viability may be limited by smaller fruit size and reduced market acceptance. Nevertheless, this genotype warrants further investigation from a nutraceutical perspective. While nutrient and biocompound analyses were beyond the scope of this study, existing evidence suggests that moderate water stress can enhance phytochemical biosynthesis (Suparmaniam et al. 2024; Alum et al. 2025), potentially improving the nutritional and therapeutic value of bitter melon fruits (Close and McArthur 2002).

From a water resource management perspective, conventional full irrigation practices typically maximize short-term yields but often compromise water-use efficiency and long-term sustainability. Our findings indicate that maintaining soil moisture at approximately 65% of field capacity preserved over 80% of potential yield while substantially reducing water consumption. This level of regulated deficit irrigation represents an optimal balance between yield performance and resource conservation. The adoption of such precision irrigation strategies could enhance both economic viability and environmental sustainability in bitter melon production systems facing increasingly limited freshwater availability. However, the long-term implications of sustained deficit irrigation on soil health remain insufficiently characterized. Prolonged maintenance at 65% field capacity may alter soil physical properties, microbial communities, and nutrient cycling dynamics. Therefore, comprehensive evaluation of these irrigation practices within an integrated soil-plant-water framework is essential to ensure both productivity and agroecosystem integrity over extended cultivation periods.

Collectively, these findings illustrate that integrating wild germplasm with optimized deficit irrigation not only enhances drought resilience but also contributes to sustainable water and soil management in tropical vegetable systems. Such an integrated approach provides a realistic pathway toward achieving climate-smart and resource-efficient crop production.

In conclusion, deficit irrigation significantly influenced the growth, physiological performance, and yield of bitter melon (*M. charantia*) under dry-season conditions in Vietnam. The wild type exhibited higher drought resilience than the cultivated type, maintaining leaf retention, chlorophyll stability, and yield at 65% Field Capacity (FC). Both types showed considerable yield reduction under severe deficit (50% FC), with the wild type being less affected. Maintaining soil moisture at 65% FC was identified as the most effective irrigation regime to sustain yield performance and optimize water use in bitter melon production. These results highlight the potential of wild bitter melon as a genetic resource for breeding drought-resilient cultivars and suggest that moderate deficit irrigation can contribute to sustainable vegetable production in water-limited environments.

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REFERENCES

Abdelraouf RE, Ghanem HG, Bukhari NA, El-Zaidy M. 2020. Field and modeling study on manual and automatic irrigation scheduling under deficit irrigation of greenhouse cucumber. Sustainability 12 (23): 9819. DOI: 10.3390/su12239819.

Alhariri A, Behera TK, Jat GS, Devi MB, Boopalakrishnan G, Hemeda NF, Teleb AA, Ismail E, Elkordy A. 2021. Analysis of genetic diversity and population structure in bitter gourd (*Momordica charantia* L.) using morphological and SSR markers. Plants (Basel) 10 (9): 1860. DOI: 10.3390/plants10091860.

Alum EU, Udechukwu CD, Obasi DC. 2025. RNA signaling in medicinal plants: An overlooked mechanism for phytochemical regulation. Biochem Biophys Rep 42: 102032. DOI: 10.1016/j.bbrep.2025.102032.

Champaneri DD, Desai KD, Sharma V, Madane DA, More SJ. 2024. A synoptic review of deficit irrigation methods: Sustainable water-saving strategies in vegetable cultivation. Water Supply 24 (9): 3132-3147. DOI: 10.2166/ws.2024.195.

Close DC, McArthur C. 2002. Rethinking the role of many plant phenolics-protection from photodamage not herbivores? Oikos 99 (1): 166-172. DOI: 10.1034/j.1600-0706.2002.990117.x.

Cui J, Yang Y, Luo S, Wang L, Huang R, Wen Q, Han X, Miao N, Cheng J, Liu Z, Zhang C, Feng C, Zhu H, Su J, Wan X, Hu F, Niu Y, Zheng X, Yang Y, Shan D, Dong Z, He W, Dhillon NPS, Hu K. 2020. Whole-genome sequencing provides insights into the genetic diversity and domestication of bitter gourd (*Momordica* spp.). Hortic Res 7 (1): 85. DOI: 10.1038/s41438-020-0305-5.

Fereres E, Soriano MA. 2007. Deficit irrigation for reducing agricultural water use. J Exp Bot 58 (2): 147-159. DOI: 10.1093/jxb/erl165.

Geerts S, Raes D. 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. Agric Water Manag 96 (9): 1275-1284. DOI: 10.1016/j.agwat.2009.04.009.

Jayaraj MS, Beevy SS. 2021. Impact of drought on the characteristic attributes in the varieties of *Momordica charantia* L. Intl J Botany Stud 6 (3): 125-131.

Kafle A, Singh S, Singh M, Bajwa P, Deb S, Simpson C, Ritchie G. 2025. Influence of deficit irrigation and biochar amendment on growth, physiology, and yield of cucumber in West Texas. Sci Rep 15: 9615. DOI: 10.1038/s41598-025-94113-y.

Kaman H, Özbek Ö, Polat E. 2023. Determination of the effect of different irrigation regimes on some quality properties of cucumber. Tekirdağ Ziraat Fakültesi Dergisi 20 (2): 318-333. DOI: 10.33462/jotaf.1093951.

Kapazoglou A, Gerakari M, Lazaridi E, Kleftogianni K, Sarri E, Tani E, Bebeli PJ. 2023. Crop wild relatives: A valuable source of tolerance to various abiotic stresses. Plants (Basel) 12 (2): 328. DOI: 10.3390/plants12020328.

Khan MM, Al-Subhi SJ, Akram MT, Al-Busaidi W, Siddiqi SA, Farooque AA. 2024. Effect of regulated deficit irrigation on cucumber growth and fruit yield in greenhouse conditions. Agrivita 46 (3): 572-581. DOI: 10.17503/agrivita.v46i3.4555.

Kou X, Han W, Kang J. 2022. Responses of root system architecture to water stress at multiple levels: A meta-analysis of trials under controlled conditions. Front Plant Sci 13: 1085409. DOI: 10.3389/fpls.2022.1085409.

Mir E, Piri H. 2021. Effects of different levels of wheat biochar and water stress on quantitative and qualitative characteristics of Carla (bitter melon) in potted conditions. Iran J Water Res Agric 35 (2): 169-185. DOI: 10.22092/jwra.2021.352930.845. [Persian]

Ortiz R, Bassi FM, Rao M, Rubiales D. 2024. Trends and perspectives for the use of crop wild relatives in crop breeding. Front Plant Sci 15: 1424160. DOI: 10.3389/fpls.2024.1424160.

Palada MC, Chang LC. 2003. Suggested cultural practices for bitter gourd. AVRDC International Cooperators' Guide, Publication No. 03-547. AVRDC, Shanhua, Taiwan. Available at: https://worldveg.tind.io/record/39432?utm_source=chatgpt.com&v=pdf

Parkash V, Singh S, Deb SK, Ritchie GL, Wallace RW. 2021. Effect of deficit irrigation on physiology, plant growth, and fruit yield of cucumber cultivars. Plant Stress 1: 100004. DOI: 10.1016/j.stress.2021.100004.

Pham TMH, Ngo DH, Ngo DN, Vo TS. 2019. Investigation of biological activities of wild bitter melon (*Momordica charantia* Linn. var. abbreviata Ser.). Biomolecules 9 (6): 211. DOI: 10.3390/biom9060217.

Rojas-Sandoval J, Acevedo-Rodríguez P. 2014. *Momordica charantia* (Bitter Gourd). CABI Compendium, Wallingford. DOI: 10.1079/cabicompendium.34678.

Singh M, Singh P, Singh S, Saini RK, Angadi SV. 2021. A global meta-analysis of yield and water productivity responses of vegetables to deficit irrigation. Sci Rep 11: 22095. DOI: 10.1038/s41598-021-01433-w.

Suparmaniam U, Lam MK, Lim JW, Tan IS, Chin BLF, Shuit SH, Lim S, Pang YL, Kiew PL. 2024. Abiotic stress as a dynamic strategy for enhancing high-value phytochemicals in microalgae: Critical insights, challenges and future prospects. Biotechnol Adv 70: 108280. DOI: 10.1016/j.biotechadv.2023.108280.

Waqas M, McCouch SR, Francioli D, Tringe SG, Manzella D, Khoury CK, Rieseberg LH, Dempewolf H, Langridge P, Geilfus CM. 2025. Blueprints for sustainable plant production through the utilization of crop wild relatives and their microbiomes. Nat Commun 16 (1): 6364. DOI: 10.1038/s41467-025-61779-x.