International Journal of Plant & Soil Science

Volume 37, Issue 12, Page 359-371, 2025; Article no.IJPSS.149787
ISSN: 2320-7035

Stomatal Conductance and Leaf Temperature Responses of Cucumber (*Cucumis sativus* L.) to Deficit Drip Irrigation Under Tropical Conditions

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2025/v37i125898

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/149787

Original Research Article

Received: 12/10/2025
Accepted: 17/12/2025
Published: 26/12/2025

ABSTRACT

Water scarcity threatens sustainable vegetable production in tropical regions, which necessitates water-efficient irrigation strategies. This study evaluated physiological responses of cucumber (*Cucumis sativus* L.) to deficit drip irrigation under tropical field conditions in Ogbomoso, Nigeria. A

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Cite as: *Onofua, O.E., Abegunrin, T.P., Awe, G.O., Adejumobi, M.A., Letuma, P., Sebitia, M., Adeosun, B.A, Aderinto, F.A., Adebayo, T.B., and Adesoye, I.O. 2025. "Stomatal Conductance and Leaf Temperature Responses of Cucumber (Cucumis Sativus L.) to Deficit Drip Irrigation Under Tropical Conditions". International Journal of Plant & Soil Science 37 (12):359–371. https://doi.org/10.9734/ijpss/2025/v37i125898.*

split-plot randomized complete block design tested three irrigation depths (100%, 85%, and 70% of crop evapotranspiration) as main plots and three irrigation intervals (1, 2, and 3 days) as subplots. Stomatal conductance and leaf temperature were measured weekly from 4 to 8 weeks after planting across vegetative and reproductive stages. Irrigation depth significantly affected both physiological parameters at critical growth stages ($p < 0.05$), while irrigation interval showed no significant effects. At 5 weeks after planting, deficit irrigation reduced stomatal conductance by 21.6-26.8% compared to full irrigation, indicating water stress during early reproduction. Unexpectedly, moderate deficit irrigation (85% crop evapotranspiration) exhibited 0.9-1.3°C lower leaf temperatures than full irrigation at multiple growth stages, suggesting enhanced thermoregulatory capacity through optimized stomatal regulation. By 6 weeks, moderate deficit showed the highest stomatal conductance among treatments, indicating adaptive physiological responses. Late-stage convergence of physiological parameters demonstrated successful acclimation to water deficit. Results support moderate deficit irrigation (85% crop evapotranspiration) as a viable water-saving strategy for tropical cucumber production, potentially reducing irrigation requirements by 15% while maintaining favourable physiological status. Irrigation scheduling flexibility (1-3day intervals) offers practical advantages for resource-constrained farmers without compromising plant function.

Keywords: Deficit irrigation; cucumber; stomatal conductance; leaf temperature; water use efficiency; tropical agriculture.

1. INTRODUCTION

Water scarcity is one of the most serious challenges to agricultural sustainability in tropical regions, especially in sub-Saharan Africa. Climate variability, population growth, and competing water demands continue to threaten food security (Adeoti et al., 2023; FAO, 2023). In Nigeria, agriculture depends heavily on freshwater withdrawals. However, water availability for irrigation remains severely limited because of unreliable rainfall, poor infrastructure, and frequent droughts, with over 1,250 hectares of farmland affected by water scarcity in recent years (Associated Press, 2025; World Bank, 2025). Climate variability and inadequate irrigation infrastructure continue to threaten agricultural productivity and food security (Adeyolanu & Okelola, 2024; Akanbi et al., 2025). With projections showing increasing water stress across West African farming systems, water-efficient irrigation strategies are needed to maintain crop productivity while conserving limited water resources (Adeyolanu & Okelola, 2024).

Cucumber (*Cucumis sativus* L.) is an important vegetable crop widely cultivated in tropical and subtropical regions for its nutritional and economic value. Yet, its production faces major constraints under limited water supply because of its shallow root system (20–30 cm), high transpiration rate, and high-water demand during the growing season (Çeliktopuz et al., 2025; Raphael et al., 2025). Despite these challenges, cucumber has moderate tolerance to water stress. This feature creates opportunities for deficit irrigation (DI) strategies that save water while maintaining acceptable yields (Parkash et al., 2021; Kumar et al., 2024).

Evidence from recent studies shows that moderate deficit irrigation can enhance water use efficiency (WUE) in cucumber without severe yield penalties. Kafle et al. (2025) demonstrated that applying 80% ETc before mid-season and 60% ETc afterward reduced water use by 22–27% with only a 14% average yield loss relative to full irrigation (100% ETc). This performance was linked to sustained stomatal conductance, photosynthetic activity, and leaf area development. Greenhouse studies further confirm that while full irrigation maximises yield, moderate deficits around 80% ETc provide feasible options for water-limited environments, achieving water productivity as high as 65.4 kg/m³ with subsurface drip systems using 2 L/h emitters (Masria et al., 2021). According to Masria et al. (2021), 80% ETc drip irrigation typically produces water productivity values of 50–60 kg/m³, with subsurface systems outperforming surface drip. In contrast, irrigation below 70% ETc often leads to major yield reductions, as shown by Peter et al. (2024), who reported yield declines to 6,400–6,778 kg/ha and 4,133–4,822 kg/ha when deficits occurred at 5–7 and 7–9 weeks after planting, respectively, compared with 14,400 kg/ha under full irrigation. These results emphasize the need for carefully calibrated DI that balances water savings with yield stability.

Studies from arid regions provide additional support for DI strategies in cucumber. Alomran et al. (2024) showed that partial root-zone drying (PRD) and regulated deficit irrigation (RDI) applied through surface and subsurface drip systems improved water savings while maintaining high yields in both greenhouse (up to 13.8 kg/m² under PRD–subsurface irrigation in winter) and open-field production in Saudi Arabia. Likewise, Kafle et al. (2025) found that moderate DI (e.g., 80% ETc early, 60% later), combined with biochar amendments (15–20 t/ha), mitigated stress effects on cucumber physiology and yield in semi-arid West Texas, saving 25% water with only 14% yield loss, although biochar had limited short-term impacts.

Physiological indicators provide important insights for designing effective DI strategies (Savvides et al., 2012; Parkash et al., 2021). Stomatal conductance, a key regulator of gas exchange and transpiration, typically declines under water deficit as a water-saving mechanism controlled by changes in leaf water potential and abscisic acid signalling. Reduced stomatal aperture decreases transpirational cooling and photosynthetic CO_2 uptake, often elevating leaf temperature and reducing productivity (Olorunwa et al., 2022). The interaction between stomatal behaviour and photosynthesis is complex: Olorunwa et al. (2022) reported that reduced CO_2 assimilation in stressed cucumber seedlings resulted from both limited stomatal conductance and biochemical constraints, including declines in Rubisco activity and electron transport. Savvides et al. (2012) also highlighted the coordinated roles of hydraulic and stomatal conductances in shaping photosynthetic responses under osmotic stress.

Water use efficiency, expressed as yield or biomass per unit of water used, is a key measure of irrigation performance. Severe stress can lower WUE because plants fix less carbon for each unit of water lost. In contrast, moderate stress can improve WUE through better stomatal regulation and osmotic adjustment (Kafle et al., 2025).

Drip irrigation systems enhance WUE by delivering water directly to the root zone and minimizing evaporative losses (FAO, 2023). Their effectiveness, however, depends heavily on irrigation depth and scheduling. Hokam et al. (2011) showed that irrigation frequency strongly affects soil moisture distribution, nutrient availability, yield, and WUE in maize under arid conditions, with shorter irrigation intervals generally improving WUE. For vegetable crops, irrigation interval significantly influences physiological processes, growth, yield, and WUE. Puértolas et al. (2020) noted that frequency effects at constant irrigation volumes are often underestimated despite their importance. França et al. (2024) emphasized that optimal scheduling must minimize water use while meeting crop water requirements. He et al. (2025) further demonstrated that well-managed fertigation improved cucumber productivity, WUE, and fruit quality by enhancing photosynthesis and stomatal performance.

In Nigeria, adoption of water-efficient irrigation systems among smallholder farmers is a vital step toward improving resilience and productivity under limited water supply. The Nigerian government and FAO have promoted drip irrigation technology to strengthen food security, with recent initiatives modernizing irrigation systems and providing training to expand irrigated farmland to over 15,000 hectares in some states (World Bank, 2025). However, effective use of such systems requires local data on how crops respond physiologically to different irrigation regimes (Akanbi et al., 2025).

Despite cucumber's growing economic importance and increasing interest in water-saving irrigation, few field studies have examined its physiological responses to deficit drip irrigation under tropical Nigerian conditions. Most existing research has been conducted in temperate climates or greenhouse environments, which differ substantially from tropical conditions characterized by high temperatures, intense solar radiation, and elevated vapour pressure deficits. Moreover, the combined effects of irrigation depth and interval on cucumber physiology remain poorly understood, limiting the development of locally appropriate irrigation guidelines (Akanbi et al., 2025).

To address these gaps, the present study evaluated the physiological responses of field-grown cucumber to different deficit irrigation levels and irrigation intervals in a tropical Nigerian environment. The specific objectives were to: (1) determine the effects of deficit irrigation at 85% and 70% ETc relative to full irrigation (100% ETc) on stomatal conductance and leaf temperature across growth stages, and (2) assess whether irrigation intervals (daily, every 2 days, or every 3 days) influence these physiological traits. The findings aim to inform sustainable irrigation management strategies that maintain cucumber productivity and physiological performance under water-scarce tropical conditions (FAO, 2023).

2. MATERIALS AND METHODS

2.1 Experimental Site

The study was conducted during the 2023 growing season at the Teaching and Research Farm of the Department of Agricultural and Biosystems Engineering, Ladoke Akintola University of Technology (LAUTECH), Ogbomoso, Oyo State, Nigeria. The experimental site is located at latitude 8°10'06" N and longitude 4°16'12" E, with an elevation of 341 meters above mean sea level. The region experiences a tropical wet-and-dry climate characterized by distinct wet (April-October) and dry (November-March) seasons, with mean annual rainfall of approximately 1,250 mm and mean annual temperature of 27°C. Prior to the experiment, composite soil samples were collected from 0-30 cm depth across the experimental area and analysed for physicochemical properties following standard procedures. The soil was sandy loam (65% sand, 20% silt, 15% clay) with pH 6.4, organic matter content of 2.1%, and field capacity of 0.28 cm^3/cm^3.

2.2 Experimental Design and Treatment Structure

A randomised complete block design (RCBD) with a split-plot arrangement was used and replicated three times (SARE, 2017). This design was suitable because irrigation depth required larger plots for uniform water distribution, while irrigation interval could be managed within smaller subplots (Saranya et al., 2024). The main plot factor was irrigation depth based on crop evapotranspiration (ETc) at three levels: D1 (100% ETc, full irrigation as control), D2 (85% ETc, moderate deficit), and D3 (70% ETc, severe deficit). The subplot factor was irrigation interval at three levels: I1 (1-day interval, daily irrigation), I2 (2-day interval), and I3 (3-day interval). These factors produced nine treatment combinations replicated across three blocks, giving 27 experimental units. Each unit measured 0.9 m × 3 m (2.7 m²). A 1 m buffer separated adjacent plots to prevent lateral water movement and cross-contamination.

2.3 Crop Establishment and Management

The cucumber cultivar 'DARINA F1' (hybrid indeterminate type) was selected based on its widespread cultivation in southwestern Nigeria and documented suitability for tropical conditions. Prior to sowing, the field was prepared through conventional tillage operations including ploughing to 30 cm depth followed by harrowing. Poultry manure was applied at 5 t/ha two weeks before planting to enhance soil organic matter and water-holding capacity. Seeds were manually sown at 2-3 cm depth with intra-row spacing of 30 cm and inter-row spacing of 90 cm, achieving a plant population density of approximately 37,000 plants/ha. Thinning was performed at 14 days after planting (DAP) to maintain one vigorous seedling per stand. Weed control was accomplished through manual weeding at the appropriate times to ensure weed-free conditions throughout the experimental period. Integrated pest management practices were uniformly applied across all treatments.

2.4 Irrigation System and Management

A drip irrigation system was installed to deliver precise water volumes according to treatment requirements. The daily crop water requirement (ETc) was derived from the FAO ETo Calculator using the FAO Penman–Monteith equation.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where ETo is reference evapotranspiration (mm/day), Rn is net radiation at the crop surface (MJ/m²/day), G is soil heat flux (MJ/m²/day), T is mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (m/s), es is saturation vapour pressure (kPa), ea is actual vapour pressure (kPa), Δ is the slope of the vapour pressure curve (kPa/°C), and γ is the psychrometric constant (kPa/°C) (Allen et al., 1998).

Crop evapotranspiration (ETc) was obtained using:

$$ET_c = K_c \times ET_o \quad (2)$$

The crop coefficients (Kc) were 0.45 (initial stage), 0.70 (crop development), 0.90 (mid-season), and 0.75 (late season), following FAO-56 guidelines adjusted to local conditions.

A pressure-compensating inline drip system was used to maintain uniform flow across all units. The system consisted of a main supply line (50 mm PVC), submains (50 mm), and laterals (16 mm polyethylene tubes) with emitters spaced 30 cm apart. Each emitter discharged 2.0 L/h. Flow control valves were fitted at each plot inlet for independent scheduling and accurate volume measurement.

Irrigation treatments started at 14 DAP. The irrigation volume for each treatment was computed as:

$$V = ET_c \times A \times D_f \quad (3)$$

where V is irrigation volume (L), A is plot area (m²), and Df is the deficit factor (1.0, 0.85, or 0.70 for D1, D2, and D3, respectively). For the 2-day and 3-day intervals, the cumulative ETc over the interval was applied in one irrigation to ensure equal total water amounts at each depth level.

2.5 Physiological Measurements

Physiological data were collected at 2-week intervals from 28 DAP (4 weeks after planting) to 56 DAP (8 weeks after planting). These periods covered the vegetative, flowering, and early fruiting stages. Measurements took place between 11:00 and 14:00 hours (local time) under clear skies to capture peak stress conditions and maintain consistency (Pietragalla & Pask, 2012). Three plants were selected randomly from the central rows of each plot and tagged for repeated observations.

Stomatal conductance was measured with an SC-1 Leaf Porometer (METER Group, Inc., Pullman, WA, USA) using the steady-state diffusion method (METER Group, 2018). Measurements were taken on the lower surfaces of fully expanded healthy leaves from the upper canopy (third or fourth leaf from the tip). The sensor head was placed gently on the leaf to seal the aperture without damaging tissue. The device operated in Auto Mode, which uses a predictive algorithm to compute steady-state conductance within 30 seconds. Three readings per plant (nine per plot) were averaged and expressed in mmol m^{-2} s^{-1}.

Leaf temperature was recorded with the porometer's built-in sensor at the same time and on the same leaves. The sensor measured temperature through direct contact with ±0.5°C precision. Three readings per plant were averaged to obtain plot-level mean values, expressed in °C.

2.6 Data Analysis

The data collected were analysed using SPSS version 25. Analysis of variance (ANOVA) was used to test treatment effects and interactions. Mean separation was done using the least significant difference (LSD) test at a 5% probability level.

3. RESULTS

3.1 Stomatal Conductance Responses

The effects of irrigation depth and interval on cucumber stomatal conductance from 4 to 8 WAP are presented in Figs. 1 and 2, respectively.

3.1.1 Effect of irrigation depth

Stomatal conductance exhibited significant temporal variation in response to irrigation depth across the five measurement periods (Fig. 1). At 4 weeks after planting (WAP), stomatal conductance values ranged from 977.1 to 1423.0 mmol m^{-2} s^{-1} across irrigation depths, with no statistically significant differences observed ($p > 0.05$). Notably, deficit irrigation treatments D2 (85% ETc) and D3 (70% ETc) exhibited numerically higher stomatal conductance (1423.0 and 1413.8 mmol m^{-2} s^{-1}, respectively) compared to full irrigation D1 (100% ETc, 977.1 mmol m^{-2} s^{-1}), though this difference did not reach statistical significance.

By 5 WAP, corresponding to the early reproductive stage, significant differences emerged among irrigation depths ($p < 0.05$). Full irrigation (D1) maintained the highest stomatal conductance at 979.8 mmol m^{-2} s^{-1}, which was significantly greater than both D2 (768.2 mmol m^{-2} s^{-1}) and D3 (717.5 mmol m^{-2} s^{-1}), representing reductions of 21.6% and 26.8%, respectively. This pattern indicated the onset of water stress responses under deficit irrigation during this critical developmental period.

At 6 WAP, an unexpected pattern emerged where moderate deficit irrigation (D2) exhibited the highest stomatal conductance at 836.7 mmol m^{-2} s^{-1}, significantly exceeding D3 (559.9 mmol m^{-2} s^{-1}, $p < 0.05$), while D1 showed an intermediate value of 692.9 mmol m^{-2} s^{-1} that did not differ significantly from either extreme. This represented a 49.4% increase in stomatal conductance for D2 compared to D3, suggesting possible physiological adaptation mechanisms under moderate water deficit.

During the late growth stages (7 and 8 WAP), no significant differences in stomatal conductance were detected among irrigation depths ($p > 0.05$), with values ranging from 661.5 to 817.0 mmol m^{-2} s^{-1}. This convergence of stomatal responses across treatments indicated acclimation of cucumber plants to the imposed water deficit conditions by the late fruiting stage.

3.1.2 Effect of irrigation interval

Irrigation interval (1-day, 2-day, or 3-day) did not significantly affect stomatal conductance at any measurement period ($p > 0.05$ for all time points; Fig. 2). At 4 WAP, stomatal conductance showed a non-significant trend of increasing with longer irrigation intervals, ranging from 1161.9 mmol m^{-2} s^{-1} (I1, daily irrigation) to 1342.1 mmol m^{-2} s^{-1} (I2, 2-day interval) and 1309.8 mmol m^{-2} s^{-1} (I3, 3-day interval). From 5 WAP onward, this trend reversed, with stomatal conductance generally decreasing as irrigation interval increased, though differences remained statistically non-significant. At 8 WAP, for example, stomatal conductance values were 738.8, 715.8, and 823.8 mmol m^{-2} s^{-1} for I1, I2, and I3, respectively, showing a numerical variation without statistical significance.

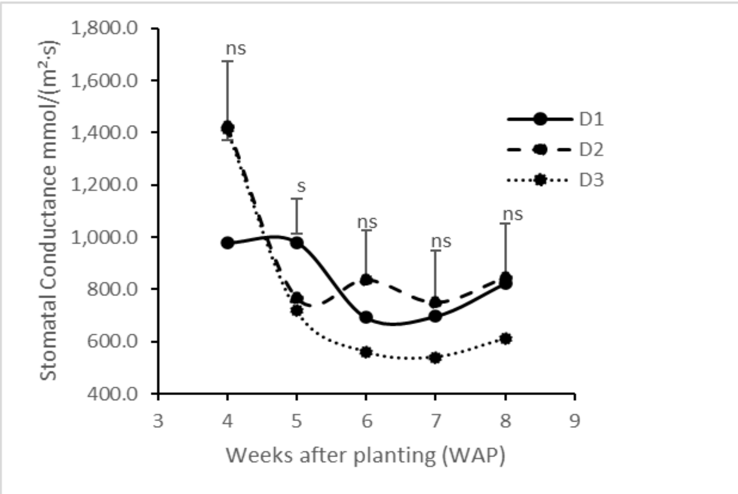

Fig. 1. Temporal changes in stomatal conductance across irrigation depths
s – significant; ns – nonsignificant

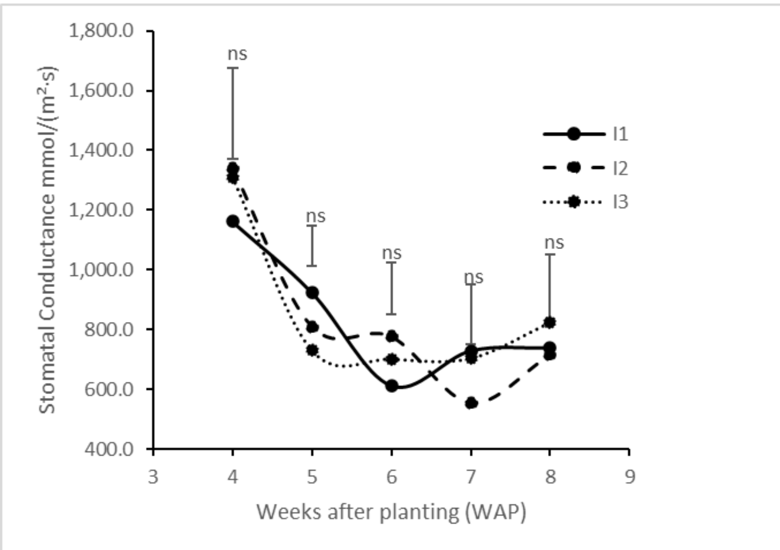

Fig. 2. Temporal changes in stomatal conductance across irrigation intervals
s – significant; ns – nonsignificant

3.2 Leaf Temperature Responses

The effects of irrigation depth and interval on cucumber leaf temperature from 4 to 8 WAP are presented in Figs. 3 and 4, respectively.

3.2.1 Effect of irrigation depth

Leaf temperature demonstrated significant responses to irrigation depth at multiple growth stages (Fig. 3). At 4 WAP, leaf temperatures were uniformly high across all treatments (39.1-39.9°C) with no significant differences ($p > 0.05$). However, significant differences emerged at 5 WAP ($p < 0.05$), where moderate deficit irrigation (D2) exhibited the lowest leaf temperature at 37.2°C, significantly lower than both D1 and D3 (both 38.1°C), representing a 0.9°C reduction.

This pattern of D2 maintaining lower leaf temperatures persisted at 6 WAP, where D2 recorded 38.3°C, significantly lower than D1 (39.6°C, $p < 0.05$), while D3 showed an intermediate value of 39.2°C. The temperature differential between D1 and D2 at this stage reached 1.3°C, which is physiologically meaningful in terms of metabolic function and stress avoidance.

At 7 WAP, leaf temperatures converged across irrigation depths (38.8-39.5°C) with no significant differences ($p > 0.05$). However, significant differences re-emerged at 8 WAP ($p < 0.05$), where D2 again displayed the lowest temperature at 37.8°C, significantly lower than D3 (39.2°C), with D1 showing an intermediate value of 38.3°C. The consistent pattern of lower leaf temperatures under moderate deficit irrigation (85% ETc) across multiple growth stages suggested enhanced thermoregulatory capacity under this irrigation regime.

3.2.2 Effect of irrigation interval

Similar to stomatal conductance, irrigation interval exerted no significant effect on leaf temperature throughout the experimental period ($p > 0.05$ for all measurement dates; Fig. 4). Leaf temperatures remained relatively consistent across irrigation intervals at each measurement period, ranging from 37.7°C to 39.7°C across all growth stages. At 5 WAP, for instance, leaf temperatures were 37.8°C (I1), 37.7°C (I2), and 37.8°C (I3), demonstrating virtually no variation among irrigation frequencies. This stability in leaf temperature across different irrigation intervals aligned with the stomatal conductance results, suggesting that cucumber maintained similar thermoregulatory function regardless of whether water was applied daily or at 2-3 day intervals, provided total water input remained constant.

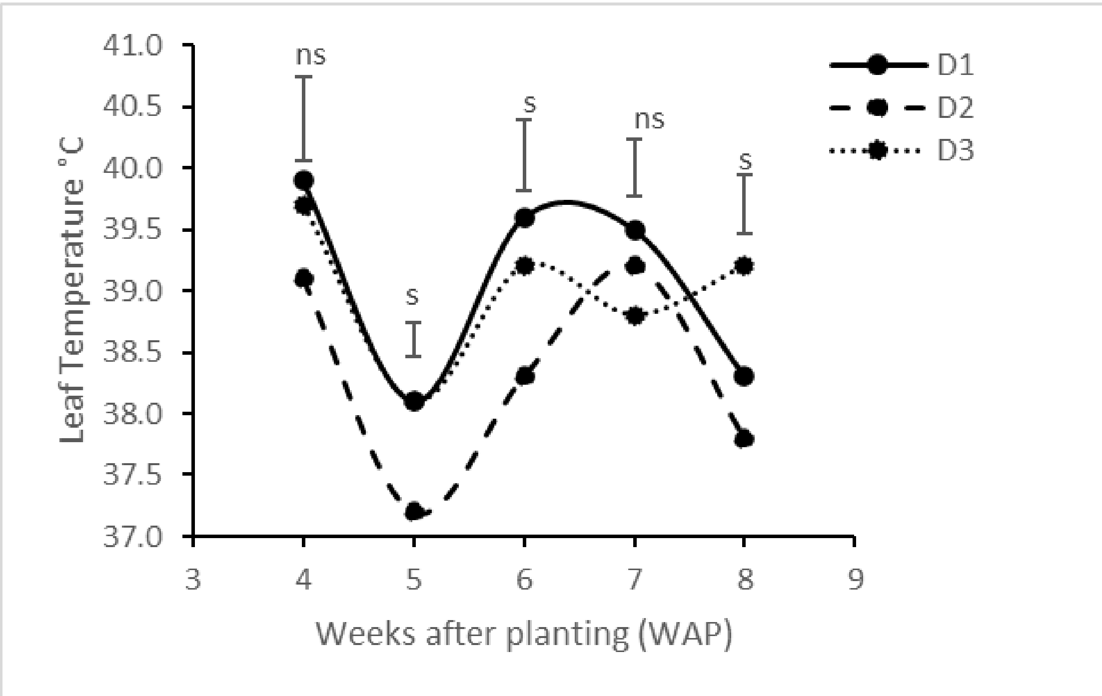

Fig. 3. Temporal changes in leaf temperature across irrigation depths
s – significant; ns – nonsignificant

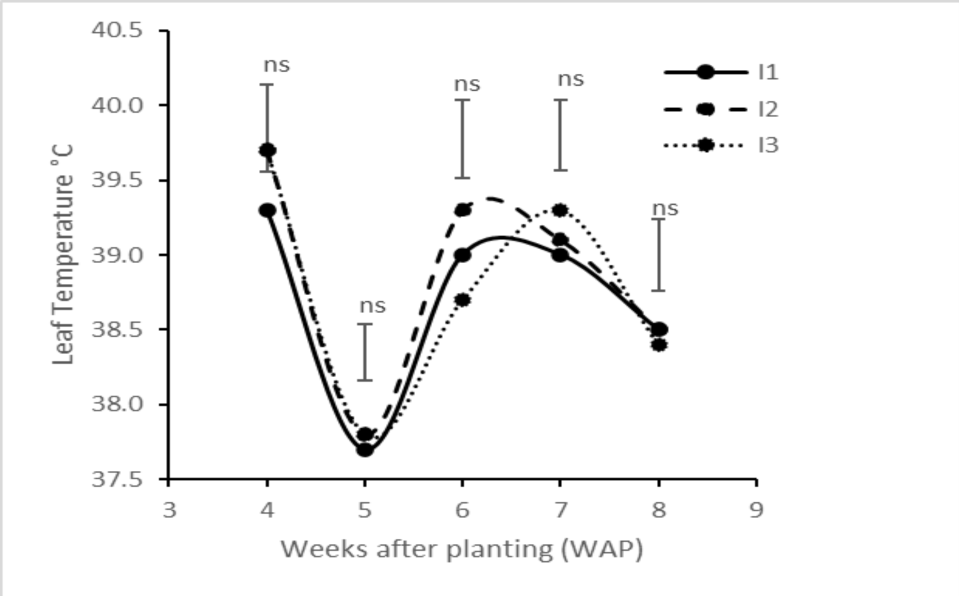

Fig. 4. Temporal changes in leaf temperature across irrigation intervals
s – significant; ns – nonsignificant

3.3 Temporal Patterns

Both physiological parameters exhibited distinct temporal dynamics across the growth cycle. Stomatal conductance generally declined from 4 WAP to later growth stages, with mean values across all treatments decreasing from approximately 1270 mmol m^{-2} s^{-1} at 4 WAP to approximately 713 mmol m^{-2} s^{-1} at 8 WAP. This 44% reduction likely reflected normal physiological changes in leaf age and canopy development. Leaf temperature showed less pronounced temporal variation, fluctuating between 37°C and 40°C across the measurement period, with the highest temperatures generally occurring at 4 and 6 WAP, which coincided with periods of rapid vegetative growth and early reproductive development.

4. DISCUSSION

4.1 Stomatal Conductance Responses to Deficit Irrigation

Stomatal conductance patterns observed in this study demonstrate dynamic physiological adaptations of cucumber to water deficit under tropical field conditions. The unexpectedly higher stomatal conductance recorded under deficit irrigation treatments (D2 and D3) at 4 WAP contradicts typical drought responses where water shortage generally causes stomatal closure to reduce water loss. Nour et al. (2024) reported that drought typically induces stomatal closure as an initial response to limit transpiration and stabilise shoot water status. However, this early-stage response in the present study likely reflects developmental factors, as at 4 WAP, limited leaf area development may not have generated sufficient transpirational demand to manifest water deficit impacts during vegetative establishment.

The marked decline in stomatal conductance at 5 WAP under deficit irrigation aligns with the expected water stress response. This period corresponds to the early reproductive stage, a phase when cucumber is particularly sensitive to reduced water availability. Similar findings have been reported by Peter et al. (2024), who noted significant yield losses when irrigation deficits occurred at this stage. Stomatal closure conserves water but restricts CO_2 entry, reducing photosynthetic efficiency and potentially affecting flower and fruit development (Nour et al., 2024).

At 6 WAP, moderate deficit irrigation (D2, 85% ETc) showed the highest stomatal conductance, exceeding both full irrigation (D1) and severe deficit (D3). This pattern indicates an adaptive response where mild stress stimulates physiological adjustment that improves function under limited water supply. Three mechanisms may explain this outcome. First, moderate deficit can promote deeper root growth and greater hydraulic conductivity, which enhances water uptake despite lower soil moisture (Parkash et al., 2021). Second, osmotic adjustment through the accumulation of compatible solutes may help maintain cell turgor and stomatal activity at lower water potentials. Third, moderate deficit may improve water use efficiency by optimising the balance between transpiration and CO_2 assimilation.

The convergence of stomatal conductance across treatments at 7–8 WAP suggests that cucumber acclimated to the imposed deficits. This adaptation may involve several mechanisms. Stomatal development can be adjusted through ABA- and SnRK2 kinase-mediated signalling that controls stomatal density via phosphorylation of SPEECHLESS (Yang et al., 2022). Other adjustments may include higher root-to-shoot ratios, altered leaf anatomy, and metabolic changes that support essential physiological functions under limited water conditions (Osakabe et al., 2014; Kafle et al., 2025).

4.2 Leaf Temperature Regulation Under Water Deficit

The observed leaf temperature patterns demonstrate cucumber's ability to regulate temperature effectively under deficit irrigation. Transpiration serves as the primary mechanism for leaf cooling by releasing water vapor, which dissipates heat and maintains the leaf temperature within a range optimal for photosynthesis and metabolic activities (Lin et al., 2017). When transpiration is sufficient, leaf temperature typically remains 2 to 10°C cooler than the ambient air, preventing thermal damage and preserving enzyme function (Kibler et al., 2023).

Under moderate deficit irrigation (D2), leaf temperatures at 5, 6, and 8 weeks after planting were notably lower, indicating maintained evaporative cooling despite reduced water supply. This contrasts with the common trend where water deficits limit transpiration and raise leaf temperature (Çeliktopuz et al., 2025; Yin et al., 2023; Parkash et al., 2021). The D2 regime apparently enabled better thermal stability than both full irrigation (D1) and more severe deficit (D3) treatments.

This improved cooling under moderate deficit may reflect finely tuned stomatal regulation that balances conserving water with allowing enough transpiration to cool leaves (Jiang et al., 2025). Additionally, a more robust root system under moderate deficit likely supports sustained water uptake to fuel transpiration (Kafle et al., 2025; Parkash et al., 2021). Osmotic adjustments through solute accumulation help maintain leaf turgor during midday stress, supporting continued cooling (Kafle et al., 2025). Beyond transpiration, morphological features such as leaf orientation, surface reflectance, and anatomical traits further facilitate heat dissipation (Monteiro et al., 2016).

Conversely, elevated leaf temperatures observed during full irrigation (D1) at some stages may result from transient soil saturation. Such saturation can impair root respiration and reduce hydraulic conductivity, limiting water transport to leaves despite abundant soil moisture.

4.3 Irrigation Interval Effects and Scheduling Flexibility

The absence of significant effects of irrigation interval (1–3 days) on stomatal conductance or leaf temperature shows that cucumber can maintain stable physiological performance when total water input remains sufficient. This capacity suggests that the crop can withstand short-term soil moisture fluctuations through osmotic adjustment, deeper water extraction, and improved water use efficiency (Li et al., 2024).

These findings are consistent with studies on other cucurbits, which show that irrigation frequency can be reduced without yield penalties when the overall water volume remains constant (Al-Mehmdy & Fal-Issawi, 2023). Although no interaction between irrigation depth and interval appeared in this study, previous research found that irrigation scheduling interacts with irrigation depth to influence yield. For example, daily irrigation performed best under full irrigation (D1), two-day intervals under moderate deficit (D2), and longer intervals under severe deficit (D3). Effective irrigation management thus requires integrating irrigation depth and frequency to balance water conservation with physiological stability and yield protection.

4.4 Physiological Basis of Water Use Efficiency Enhancement

The physiological trends recorded in this study support earlier findings that deficit irrigation improves water use efficiency. Research has consistently demonstrated that moderate deficit irrigation can improve water use efficiency in cucumber production, with studies reporting improvements of 15-25% compared with full irrigation regimes (Abdou et al., 2024). The current study explains this enhancement through several physiological processes. Moderate deficit irrigation maintained stomatal regulation that limited water loss while allowing sufficient CO_2 uptake, preserved thermoregulation at critical stages, and possibly promoted deeper rooting that improved soil water extraction.

Moderate deficit therefore achieves productive water saving, in which water reduction stimulates beneficial physiological adjustments without compromising plant function. Research has consistently demonstrated that moderate deficit irrigation (80-85% ETc) can improve water use efficiency in cucumber production by 15-25% compared with full irrigation regimes through enhanced stomatal regulation, deeper root development, and osmotic adjustment. Severe deficit (70% ETc) exceeded cucumber's tolerance at some stages, as shown by reduced stomatal conductance and higher leaf temperature at 6 WAP. These responses suggest that 85% ETc provides a practical balance between water conservation and physiological stability.

4.5 Implications for Tropical Cucumber Production

For cucumber cultivation in tropical environments such as Nigeria, moderate deficit irrigation at 85% ETc offers a reliable strategy for water conservation. The high temperature, intense solar radiation, and large vapour pressure deficits characteristic of tropical climates increase evaporative demand. Under these conditions, maintaining adequate transpiration is essential for cooling and metabolic activity (Kibler et al., 2023; Lin et al., 2017, Behzadipour et al., 2024). The current findings show that cucumber can maintain favourable physiological function under 85% ETc, indicating its suitability for controlled water management.

The flexibility in irrigation scheduling also benefits smallholder farmers who often face labour and energy constraints. Applying water every two or three days instead of daily can reduce costs and operational demands without compromising crop performance. However, irrigation management should remain sensitive to developmental stages, particularly around 5 WAP, when cucumber is most vulnerable to water deficit.

5. CONCLUSION

This study shows that cucumber (*Cucumis sativus* L.) responds to deficit irrigation in a manner that depends on growth stage under tropical field conditions in Nigeria. Moderate deficit irrigation at 85% ETc sustained favourable physiological performance and produced consistently lower leaf temperatures by 0.9–1.3°C compared with full irrigation at key growth stages (5, 6, and 8 WAP). This result indicates stronger thermoregulatory capacity achieved through efficient stomatal control. Deficit irrigation reduced stomatal conductance by 21.6–26.8% at 5 WAP, which corresponds to the early reproductive stage. However, by 6 WAP, plants under 85% ETc displayed the highest stomatal conductance among treatments, showing evidence of adaptive adjustment to water limitation. Irrigation interval between one and three days did not significantly influence stomatal conductance or leaf temperature. This outcome demonstrates flexibility in irrigation scheduling that could lower operational costs for smallholder farmers. The convergence of physiological responses across all treatments in later growth stages confirmed that cucumber acclimated successfully to water deficit conditions. The findings identify moderate deficit irrigation at 85% ETc as a practical and efficient water-saving option for cucumber cultivation in tropical regions facing water scarcity. This approach can reduce irrigation input by about 15% while preserving plant physiological stability. The observed improvement in leaf temperature regulation supports earlier evidence linking moderate deficit irrigation to higher water use efficiency. Further research that combines physiological, yield, and quality analyses across different cucumber cultivars will improve understanding of crop adaptation under water-limited conditions and guide more precise irrigation recommendations for tropical production systems.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/149787