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Water Stress Effects on Physiological Responses, Water Use Efficiency and Yield of Cayenne Pepper (Capsicum annuum L) Under Screen-House Conditions

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ABSTRACT

Water stress is a major abiotic constraint limiting pepper productivity in tropical and sub-tropical environments, particularly under protected cultivation where irrigation scheduling determines plant water status. This study assessed Water Stress Effect on Growth, Yield and Water Storage Dynamics in Cayenne Pepper under screen house conditions. The experiment consisted of three watering regimes: No Stress (NS, 100% field capacity), Mild Stress (MS, 60% FC), and Severe Stress (SS, 40% FC), arranged in a Completely Randomized Design with three replications. Results showed that CWS decreased significantly from 215.6 m/Lplant under (NS) to 162.7 m/Lplant under (SS), indicating reduced plant water status under stress while relative water content declined from 86.4% (NS) to 61.3% (SS), indicating reduced plant water status under stress Water use efficiency (WUE) was highest under mild stress (4.85kg/m3) compared to NS (3.12kg/m3) and SS (2.01kg/m3). Proline accumulation (which is an amino acid that accumulates in plant tissues under stress conditions) increased significantly with stress, from 1.6(µmol/g FW (NS) to 7.8(µmol/g FW (SS), reflecting osmotic adjustment. Malondialdehyde (MDA) (which is a marker of cellular damage) also increased from 2.1 nmol/g (NS) to 6.9 nmol/g (SS), indicating enhanced lipid peroxidation under stress. Antioxidant activity (which is enzyme activities that protect plants from oxidative damage) increased progressively from 18.5(%) (NS) to 36.8(%) (SS). Leaf area declined under severe stress (318.4 cm²), while chlorophyll index remained stable under mild stress (59.8 Mg/g). Fruit yield was highest under NS (1.31 t/ha) and lowest under SS (0.81 t/ha). The study concluded that mild water stress improved physiological efficiency and WUE, while severe stress reduced productivity. Moderate irrigation is therefore recommended for optimal pepper production in derived savanna environments.

1 Introduction

Cayenne pepper (Capsicum annuum) is an economically important vegetable crop widely cultivated for its culinary, nutritional, and medicinal value. It is particularly valued for its high vitamin C, and antioxidant content (Clark, & Lee, 2016). However, pepper production is highly sensitive to soil moisture fluctuations due to its shallow root system and high transpirational demand. In many developing countries, increasing water scarcity and erratic rainfall patterns

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necessitate efficient water management strategies, especially under screen house and greenhouse cultivation. Water stress influences plant growth by altering cell turgor, stomatal conductance, photosynthetic efficiency, and assimilate translocation (Borsato, et al, 2021). Crop Water Storage (CWS) reflects the plant's ability to retain water within its tissues and serves as a direct indicator of plant water status (Fahad et al, 2017). Water Use Efficiency (WUE) integrates biomass or yield production with water consumption and is a critical index for evaluating irrigation efficiency under stress conditions (Blum, 2017).

Water stress is a major limiting factor affecting crop productivity in tropical and subtropical regions, particularly in the derived savanna agro-ecology of Nigeria. It influences plant physiological processes such as photosynthesis, transpiration, and nutrient uptake (Farooq et al., 2017). In pepper, water deficit conditions alter cellular metabolism, leading to reduced growth and yield (Ashraf & Harris, 2013). Crop water storage (CWS) and water use efficiency (WUE) are critical indicators of plant adaptation to water stress. Biochemical markers such as proline and malondialdehyde (MDA) serve as stress indicators, reflecting osmotic adjustment and oxidative damage respectively (Anjum et al., 2016). Erratic rainfall patterns and prolonged dry spells in southwestern Nigeria have increased the incidence of water stress in vegetable production systems. There is limited information on how varying levels of water stress influence crop water storage, physiological traits, and yield of cayenne pepper under controlled conditions. Understanding these responses is essential for developing efficient irrigation strategies.

Functional traits such as leaf area, chlorophyll content and leaf relative water content provide insight into plant adaptive strategies under water-limited environments (Hasanuzzaman, et al, 2013). Physiologically, water stress triggers stomatal closure mediated by abscisic acid (ABA), reducing transpiration but also limiting CO_2 uptake. Biochemically, plants respond through osmolyte accumulation (proline, soluble sugars), activation of antioxidant enzymes, and membrane stabilization to mitigate oxidative stress (Farooq et al., 2020). Plants respond to water deficit through three broad strategies: drought escape (rapid lifecycle completion), avoidance (maintained tissue water status through reduced water loss or enhanced uptake), and tolerance (survival despite low tissue water potential) (Farooq et al., 2020). Pepper species generally show avoidance-oriented responses, but variation exists among cultivars. Cayenne types, with their extended fruiting period and indeterminate growth, present particular challenges for water management, prolonged stress exposure risks during fruit development, while temporary deficits might enhance quality attributes without severe yield loss (Guo, et al, 2020). Water storage capacity varies enormously across crops, from succulent species with substantial capacitance to herbaceous plants relying primarily on current uptake. For peppers, the relative contribution of stored versus acquired water to daily transpiration remains unclear, limiting our ability to model plant responses and design irrigation schedules (Blum, 2017). Cayenne pepper was selected for this study because of its economic importance, sensitivity to water stress, and relevance to protected cultivation systems where irrigation control is feasible.

2 Materials and Methods

2.1 Experimental Site

The experiment was conducted in a screen house at the Teaching and Research Farm of the Department of Crop Production Technology, Federal Polytechnic, Ado-Ekiti, Nigeria. The screen house provided controlled environmental conditions, minimizing rainfall interference while allowing natural light penetration. The screen house experiment was carried out between July and October of 2022.

2.2 Experimental Design and Treatments

The experiment was laid out in a Completely Randomized Design (CRD) with three water stress treatments and three replications:

i. No Stress (NS): 100% field capacity, watering every 2 days
ii. Mild Stress (MS): 60% field capacity, watering every 4 days
iii. Severe Stress (SS): 40% field capacity, watering every 6 days

The stress levels were selected to simulate optimal, moderate, and extreme water deficit conditions commonly experienced under field and protected cultivation systems. NS represents optimal irrigation for maximum growth. MS

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simulates regulated deficit irrigation aimed at improving WUE while SS represents drought conditions causing physiological and biochemical disruption.

2.3 Nursery Establishment and Seedling Raising

Seeds of cayenne pepper (Capsicum annuum L.) were raised in a nursery for four weeks prior to transplanting. A well-prepared nursery bed measuring 2 m × 1 m was established using topsoil mixed with well-decomposed poultry manure at a ratio of 3:1 to enhance nutrient availability and improve soil structure. Seeds were sown uniformly in shallow drills at a depth of approximately 1–2 cm, covered lightly with fine soil, and mulched with dry grass to conserve moisture and regulate temperature. Watering was carried out daily using a watering can to maintain adequate moisture for germination.

Germination commenced within 5–7 days after sowing. Seedlings were thinned to avoid overcrowding and ensure uniform growth. Light shading was provided using palm fronds to protect emerging seedlings from excessive solar radiation. Healthy and uniform seedlings at four weeks old (4–5 true leaves stage) were selected for transplanting.

2.4 Transplanting Procedure

Transplanting was carried out in the screen house using 7-liter perforated plastic pots filled with air-dried, sieved sandy loam soil. The pots were arranged based on the experimental design. Seedlings were carefully uprooted from the nursery with a ball of earth to minimize root disturbance and transplanted into the pots at one seedling per pot. Transplanting was done in the early morning hours to reduce transplant shock. Immediately after transplanting, all plants were watered to field capacity and allowed to establish for one week before the commencement of water stress treatments.

2.5 Water Stress Treatments and Irrigation Scheduling

Water stress treatments were imposed by reducing soil moisture storage (SMS) based on field capacity (FC) levels, which were determined gravimetrically prior to the experiment, then measured the effect on Crop Water Storage (CWS), growth and yield of cayenne pepper.

2.6 Soil Moisture Regime Maintenance

The water stress treatments were imposed based on soil moisture storage (SMS) in the 0–30 cm soil profile, determined gravimetrically. The experimental soil was a sandy loam with water holding capacity of 0.28 $cm^3\ cm^{-3}$ at field capacity (FC), bulk density of 1.42 $g\ cm^{-3}$, and total available water capacity of 185–210 $mm\ m^{-1}$. Seven-litre plastic pots were filled with air-dried soil to a uniform depth of 30 cm. Field capacity for the potted soil was established by saturating the pots and allowing free drainage for 48 h under cover (Reynolds, 1970). The weight at FC was recorded, and the volumetric water content at FC (0.28 $cm^3\ cm^{-3}$) corresponded to 84 mm of water in the 0–30 cm profile, calculated as WHC × depth (0.28 × 300 mm = 84 mm).

Three soil moisture regimes were therefore maintained:

i. Non-stress (NS): 100% FC, equivalent to 84 mm SMS, representing optimal water availability.
ii. Mild stress (MS): 60% FC, equivalent to 50.4 mm SMS (0.60 × 84 mm), to simulate moderate soil water deficit.
iii. Severe stress (SS): 40% FC, equivalent to 33.6 mm SMS (0.40 × 84 mm), to simulate severe soil water deficit.

The required quantity of water for each treatment was calculated based on the difference between the soil's field capacity and its current moisture content. Water was applied using a graduated measuring cylinder to ensure precision. For NS, soil moisture was maintained near optimum to support maximum physiological activity. MS involved moderate water restriction to simulate mild drought conditions, while SS imposed severe moisture limitation to induce stress responses. Soil moisture levels were monitored regularly using the gravimetric method to maintain consistency across treatments. Irrigation was applied to maintain soil moisture at 100%, 60%, and 40% field capacity for the NS, MS, and SS treatments, respectively. The corresponding water volumes were 37.8, 22.7, and 15.1 mm per irrigation, delivered at 2-, 4-, and 6-day intervals. Total water applied over the 120-day experimental period, including 30 days of nursery at 100% FC, was 2,268 m^3 for NS, 1,066 m^3 for MS, and 794 m^3 for SS.

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2.7 Weeding

Weeding was carried out manually at two-week intervals to eliminate competition for nutrients, water, and light.

Parameters Evaluated included:

Crop Water Storage (CWS)

CWS was calculated as:

CWS = Fresh Weight − Dry Weight

CWS was expressed in millimeters (mm), representing the depth of water stored within the effective crop root zone (Allen et al, 1998).

Determination of Water Use Efficiency (WUE)

The WUE was estimated as:

$$WUE = \frac{Yield}{Water\ Consumed}$$

Determination of Soil Moisture Storage (SMS)

Soil moisture storage (SMS) was calculated as:

$$\text{SMS} = \theta_v \times Z_r \times 1000$$

Where SMS is soil moisture storage (mm),
θ_v is volumetric soil water content ($m^3\ m^{-3}$),
Z_r is effective root zone depth (m) as described by Allen et al. (1998, Gardner, 1986)

Determination of Physiological and Biochemical Traits

Leaf area (LA) was estimated using the Montgomery equation: LA = 0.68 (LXW) where L and W are leaf length and maximum width.
Relative water content (RWC) was determined

RWC (%) = [(FW-DW) / (TW-DW)] ×100

Where, FW is the sample fresh weight.
TW is the sample turgid weight after 4 h in distilled water
DW is the sample dry weight at 70°C for 24 h.

Chlorophyll content was extracted in 80% acetone and calculated using Porra's equations:

$$Chl_a = 12.27A_{663.6} - 2.52A_{646.6}$$
$$Chl_b = 20.10A_{646.6} - 4.92A_{663.6}$$

expressed as mg g^{-1} FW (Arnon, 1949)
Stomatal conductance (gs) which is the rate at which water vapour exits or carbon-dioxide enters the leaf through stomata was measured using a leaf photometer on the abaxial surface of the youngest fully expanded leaf using a portable porometer between 9:00–11:00 am, expressed as mmol $m^{-2}\ s^{-1}$. (Jones, 2014).

Proline content was estimated by the Bates method. Leaf tissue was extracted in 3% sulfosalicylic acid, reacted with ninhydrin, and absorbance read at 520 nm. Proline = (µgproline mL^{-1} × mL toluene) / (115.5 × g sample), expressed as µmol g^{-1} FW. (Bates, et al, 1973).

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Antioxidant enzyme activity: SOD activity was assayed by NBT photo reduction, where one unit = 50% inhibition per mg protein. CAT activity was measured as H_2O_2 decomposition at 240 nm, calculated as U mg^{-1} protein min^{-1} using 36 mM^{-1} cm^{-1} extinction coefficient Brand-Williams et al, 1995).

MDA content was determined by TBARS assay. Absorbance was read at 532 nm and corrected for non-specific turbidity at 600 nm. MDA = $[(A_{532} - A_{600}) \times V \times 1000] / (155 \times g\ FW)$, expressed as nmol g^{-1} FW, where 155 mM^{-1} cm^{-1} is the extinction coefficient (Heath, & Packer, 1968):
Yield Parameters monitored included: Days to flowering, number of Fruit, fruit length and Total yield in t/ha.

Statistical Analysis
All data were subjected to one-way analysis of variance (ANOVA) appropriate for a Completely Randomized Design (CRD) using GenStat Statistical Software (18th Edition). Treatment means were separated using Tukey's Honestly Significant Difference (HSD) test at $p \leq 0.05$. Means sharing the same letter superscript within a row are not significantly different. ** = highly significant ($p \leq 0.01$); * = significant ($p \leq 0.05$); ns = not significant ($p > 0.05$). Standard deviation (SD), standard error of the mean (SEM), and coefficient of variation (CV %) are reported for each trait. The F-critical value at p = 0.05 with df(2, 6) = 5.14; at p = 0.01 = 10.92. Where ANOVA was significant ($p \leq 0.05$),

3 Results and Discussion

3.1 Soil/Crop Performance Relationship

Table 1 (See Appendix) show that the experimental soil was a sandy loam with pH 6.2, organic carbon 1.35%, total N 0.12%, available P 18.5 mg kg^{-1}, and exchangeable K 0.32 cmol kg^{-1}. Ca, Mg, and CEC were 3.8, 1.5, and 8.6 cmol kg^{-1}, respectively, indicating moderate fertility with adequate base status for pepper production. Physical properties included bulk density of 1.42 g cm^{-3}, porosity 46%, water holding capacity 0.28 cm^3 cm^{-3}, and infiltration rate 5.6 cm h^{-1}. Total available water capacity of the soil was 185–210 mm m^{-1}. During the experiment, soil moisture storage was maintained at 84 mm (100% FC) for non-stress, 50.4 mm (60% FC) for mild stress, and 33.6 mm (40% FC) for severe stress, based on gravimetric determination at 0–30 cm depth. The low CEC and sandy loam texture confirmed that the soil had limited buffering capacity, making it suitable for evaluating genotypic responses to water deficit without confounding effects of high nutrient or water retention.

3.2 Meteorological conditions during the experiment

Table 2 (See Appendix) presents the meteorological data for the 2022 growing season at Ado-Ekiti during the experimental period (July–October). Although the study was conducted in a screen house, ambient weather influenced evaporative demand and the frequency of irrigation required to maintain the imposed water regimes. Total rainfall declined progressively from 224 mm in August to 96 mm in October, with corresponding rainy days decreasing from 18 to 8. July and August were characterized by high rainfall (186 and 224 mm) and high relative humidity (84–86%), indicating low atmospheric evaporative demand. This period coincided with the vegetative and early flowering stages of cayenne pepper.
Mean maximum temperature ranged from 28.2 °C in August to 30.2 °C in October, while minimum temperature increased slightly from 21.5 °C to 22.8 °C. The gradual rise in temperature coupled with declining RH (from 86% in August to 78% in October) and increasing sunshine hours (from 138 h in August to 168 h in October) indicated a transition from the peak of the rainy season to early dry conditions. These changes reflect increasing atmospheric vapor pressure deficit (VPD) in September and October, the period corresponding to fruiting and fruit development stages. Higher VPD and sunshine hours would have increased potential evapotranspiration in the screen house; thereby increasing the irrigation requirement to maintain the non-stress treatment at 84 mm SMS and intensifying the severity of the mild (50.4 mm) and severe (33.6 mm) water stress treatments. Thus, although the screen house excluded direct rainfall, the prevailing meteorological conditions suggest that water stress effects observed in MS and SS plants would have been accentuated during the reproductive phase (Sept–Oct) due to higher evaporative demand, while the relatively cooler, humid conditions in July–August may have moderated stress during early growth.

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3.3 Physiological and Biochemical Traits of Cayenne Pepper

Table 3 (See Appendix) shows that water stress significantly affected all functional and yield traits of cayenne pepper. Plants under NS recorded the highest leaf area 485.2 cm², chlorophyll content 52.3 SPAD, fruit number 18.4/plant, fruit length 8.6 cm, and fruit yield 6.43 g/pot equivalent to 1.31 t/ha. MS caused moderate reductions across all parameters with leaf area 452.6 cm², chlorophyll 49.8 SPAD, fruit number 17.6, fruit length 8.2 cm, and yield 6.18 g/pot = 1.26 t/ha. SS produced the lowest values and delayed phenology: leaf area dropped to 318.4 cm², chlorophyll to 38.6 SPAD, days to flowering increased to 46 days, fruit number reduced to 11.2, fruit length to 6.5 cm, and yield declined to 3.99 g/pot = 0.81 t/ha. Compared to NS, SS reduced fruit yield by 38% on t/ha basis. The trend shows that increasing water stress progressively decreased growth, delayed flowering, and lowered productivity, indicating cayenne pepper is highly sensitive to soil moisture deficit.
In Table 4 (See Appendix), mild stress improved WUE: MS had the highest WUE (4.85 kg/ m3) despite lower CWS (198.4 mm) and SMC (50.4 mm). Plants under mild stress conserve water by reducing transpiration while maintaining yield, a classic drought acclimation response in pepper severe stress caused collapse: SS showed the lowest CWS (162.7 mm) and WUE (2.01). At 40% FC / 33.6 mm SMS, soil water was insufficient to sustain growth, so both tissue hydration and water productivity dropped. As SMS fell from 84.0 → 50.4 → 33.6 mm, CWS declined from 215.6 → 198.4 → 162.7 mm. This shows crop water storage is strongly coupled to soil water availability, but mild stress allows partial decoupling via osmotic adjustment

3.4 F-Value for Significance for all Traits

Table 5 (See Appendix), shows that all six physiological and biochemical traits were highly significantly affected by water stress treatment. WUE peaked under mild stress (MS: 4.77 kg m^{-3}), significantly exceeding both NS (3.14 kg m^{-3}) and SS (2.12 kg m^{-3}), confirming that deficit irrigation at 60% FC maximizes water productivity in Cayenne pepper. Proline and MDA increased progressively with stress intensity (NS < MS < SS), confirming escalating osmotic stress and oxidative membrane damage under progressive water deficit consistent with the findings of Bates et al. (1973) and Heath & Packer (1968) respectively. Antioxidant activity increased progressively from NS (18.75%) to MS (28.34%) to SS (36.27%), reflecting the upregulation of the plant's ROS scavenging defense system as stress intensified, a compensatory response documented by Waheed et al. (2021) in Capsicum annuum under comparable water deficit conditions. The very high F-value for WUE (F = 729.54) and antioxidant activity (F = 274.98) are among the largest recorded in this study, confirming that these physiological efficiency parameters are particularly sensitive to quantitatively defined differences in soil water availability.
All 13 traits across Tables 4 and 5 are highly significant at $p \leq 0.01$ (**). The lowest F-value recorded is 26.87 (Days to Flowering), which is still 2.5 times the F-critical at p = 0.01 (10.92), confirming highly significant treatment effects across every measured trait. The pattern 'NS = MS > SS' for yield traits confirms the agronomic viability of mild deficit irrigation, while 'NS < MS < SS' for proline, MDA, and antioxidant activity confirms progressive biochemical stress with increasing water deficit. The unique 'MS > NS > SS' pattern for WUE and chlorophyll content identifies mild stress as the optimal condition for physiological water productivity efficiency in Cayenne pepper.
Relative water content (RWC) declined significantly ($p < 0.05$) with increasing water stress, ranging from 86.4% under no stress (NS) to 61.3% under severe stress (SS). This reduction reflects decreased cellular hydration and loss of turgidity under limited water availability. Under mild stress (MS), RWC (74.8%) remained moderately high, indicating that plants were still able to maintain water balance through osmotic adjustment mechanisms such as proline accumulation. This explains why yield under MS remained comparable to NS under yield result in Table 4. Interestingly, WUE was highest under mild stress (MS = 4.85), indicating that moderate stress enhances efficient water utilization. This aligns with findings of Blum (2011), who reported that mild stress can optimize carbon assimilation relative to water loss. Proline accumulation increased significantly under stress, serving as an Osmo protectant that stabilizes proteins and membranes. The highest proline level under SS (7.8) indicates strong stress adaptation but also reflects metabolic strain (Farooq et al., 2017, Taiz et al, 2018). Crop water storage (CWS) significantly declined with increasing water stress, reflecting reduced cell turgor and water availability. This directly affects physiological processes such as stomatal conductance and photosynthesis (Farooq et al., 2017).
MDA levels increased significantly under SS, indicating lipid peroxidation and oxidative damage to cell membranes (Ashraf &Foolad, 2007). This suggests that severe stress leads to cellular injury (Anjum et al., 2016). Antioxidant activity increased progressively from NS to SS, showing activation of defense mechanisms against reactive oxygen species. This is a survival response to oxidative stress but often insufficient under prolonged severe stress conditions.

3.5 Functional and Yield Traits of Cayenne Pepper

Reduced leaf area limits light interception and photosynthesis (Taiz et al., 2018). Chlorophyll index remained stable under mild stress, suggesting that moderate stress did not impair chlorophyll synthesis. However, severe stress reduced chlorophyll due to degradation and impaired biosynthesis (Ashraf & Harris, 2013). Days to flowering increased with stress, indicating delayed phenological development due to reduced metabolic activity. According to Farooq et al reduction (2017), reduction in fruit number and length under severe stress could be as a result of impaired assimilate partitioning and reproductive failure. This confirms that severe water stress limits carbon assimilation and reduces biomass allocation to fruits (Farooq et al., 2017).

The results clearly demonstrate that water stress significantly influenced crop water storage, water use efficiency, and functional traits of cayenne pepper. Mild stress (MS) optimized physiological efficiency by maintaining adequate CWS while significantly enhancing WUE. This reflects effective stomatal regulation that reduced transpiration losses without severely limiting photosynthetic carbon assimilation. Physiologically, MS plants exhibited better leaf water retention, stable chlorophyll content, and balanced root-to-shoot growth, indicating adaptive plasticity. The increase in WUE under MS is consistent with improved transpiration efficiency and optimized carbon gain per unit water lost (Blum, 2017). Biochemically, moderate proline accumulation under MS indicates effective osmotic adjustment and membrane protection. Proline stabilizes proteins, scavenges reactive oxygen species, and maintains cellular redox balance. In contrast, excessive proline accumulation and elevated MDA levels under SS reflect severe oxidative stress and membrane lipid peroxidation, indicating cellular damage rather than tolerance (Hasanuzzaman et al., 2020). Severe stress disrupted photosynthetic machinery, reduced leaf area, and impaired assimilate translocation, leading to significant yield reduction. These findings confirm that while cayenne pepper can tolerate mild water deficit through physiological and biochemical adjustments, prolonged or severe stress overwhelms protective mechanisms.

4 Conclusion

This section describes the research design, data sources, analytical procedures, and tools employed to conduct a rigorous, data-driven evaluation of Zero Trust Architecture in mitigating insider threats across distributed enterprise networks. The methodology is structured to ensure reproducibility, objectivity, and empirical validity. Figure 1 present the methodological framework of this paper.

4.1 Recommendation

For optimal performance of cayenne pepper in the derived savanna zone, irrigation should be maintained at approximately 60% field capacity, as this level balances water conservation with efficient physiological functioning and yield stability. Farmers should avoid prolonged water stress, especially during critical growth stages such as flowering and fruit development. Water stress significantly influenced physiological, biochemical, and yield traits of cayenne pepper. Mild stress improved WUE and maintained yield stability. Severe stress caused oxidative damage, reduced growth, and significantly lowered yield.

References

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M. (1998). Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper No. 56. Food and Agriculture Organization (FAO), Rome, Italy.

Anjum, S. A., Xie, X. Y., Wang, L. C., Saleem, M. F., Man, C., & Lei, W. (2016). Morphological, physiological and biochemical responses of plants to drought stress. African Journal of Agricultural Research, 11(9), 2026–2032.

Arnon, D.I (1949):Copper enzyme in isolated chloroplast: Polyphenoloxidase in Beta vulgaris Plant Physiology, 24 (1) 1-15

Ashraf, M., & Foolad, M. R. (2007). Roles of glycine betaine and proline in improving plant abiotic stress tolerance. Environmental and Experimental Botany, 59(2), 206–216. https://doi.org/10.1016/j.envexpbot.2005.12.006

Ashraf, M., & Harris, P. J. C. (2013). Photosynthesis under stressful environments: An overview. Photosynthetica, 51(2), 163–190. https://doi.org/10.1007/s11099-013-0021-6

ISSN: 3092-9598

Bates, L.S., Waldren, R.P. &Teare, I.D. (1973): Rapid determination of free proline for water-stress studies. Plant and Soil, 39: 205-207. DOI: 10.1007/BF00018060

Barrs, H. D., &Weatherley, P. E. (1962). A re-examination of the relative turgidity technique for estimating water deficits in leaves. Australian Journal of Biological Sciences, 15(3), 413–428. https://doi.org/10.1071/BI9620413

Blum, A. (2011). Plant breeding for water-limited Environments. Springer. https://doi.org/10.1007/978-1-4419-7491-4

Borsato, E., Marinello, F., Zucaro, A., &Sartori, L. (2021). Water use and water productivity in agricultural systems: A review of the main indicators. Sustainability, 13(3), 1531. https://doi.org/10.3390/su13031531

Brand-Williams, W., Cuvelier, M.E. & Berset, C. (1995): Use of a free radical method to evaluate antioxidant activity. LWT-Food Science and Technology, 28: 25-30. DOI: 10.1016/S0023-6438(95)80008-5

Clark, R., & Lee, S. H. (2016). Anticancer properties of capsaicin against human cancer. Anticancer Research, 36(3), 837–843. https://doi.org/10.21873/anticanres.11227

Fahad, S., Bajwa, A. A., Nazir, U., Anjum, S. A., Farooq, A., Zohaib, A., Sadia, S., Nasim, W., Adkins, S., Saud, S., Ihsan, M. Z., Alharby, H., Wu, C., Wang, D., & Huang, J. (2017). Crop production under drought and heat stress: Plant responses and management options. Frontiers in Plant Science, 8, 1147. https://doi.org/10.3389/fpls.2017.01147

Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., & Basra, S. M. A. (2017). Plant drought stress: Effects, mechanisms and management. Agronomy for Sustainable Development, 29(1), 185–212. https://doi.org/10.1051/agro:2008021

Farooq, M., Romdhane, L., Rizwan, M., & Gogoi, N. (2020). Drought stress in grain legumes during reproduction and grain filling. Journal of Agronomy and Crop Science, 206(1), 11-22.

Gardner, W.H. (1986.): Water content. In: Methods of Soil Analysis, Part 1. ASA-SSSA, Madison, WI. pp. 493-544. For gravimetric/volumetric soil moisture

Gill, S. S., & Tuteja, N. (2010). Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. Plant Physiology and Biochemistry, 48(12), 909–930. https://doi.org/10.1016/j.plaphy.2010.08.016

Gomez, K. A., & Gomez, A. A. (1984). Statistical procedures for agricultural research (2nd ed.). John Wiley & Sons.

Guo, Y., Bian, Z., Zhu, C., Yang, W., Zheng, C., & Ma, Y. (2020). Physiological and transcriptome analyses of the effects of exogenous dopamine on drought tolerance in apple. Plant Physiology and Biochemistry, 156, 209–223. https://doi.org/10.1016/j.plaphy.2020.08.046

Hasanuzzaman, M., Nahar, K., Alam, M. M., Roychowdhury, R., & Fujita, M. (2013). Physiological, biochemical, and molecular mechanisms of heat stress tolerance in plants. International Journal of Molecular Sciences, 14(5), 9643–9684. https://doi.org/10.3390/ijms14059643

Hasanuzzaman, M., Bhuyan, M. H. M. B., Zulfiqar, F., Raza, A., Mohsin, S. M., Mahmud, J. A., Fujita, M., & Fotopoulos, V. (2020). Reactive oxygen species and antioxidant defense in plants under abiotic stress: Revisiting the crucial role of a universal defense regulator. Antioxidants, 9(8), 681. https://doi.org/10.3390/antiox9080681

Heath, R. L., & Packer, L. (1968). Photoperoxidation in isolated chloroplasts: I. Kinetics and Stoichiometry of fatty acid peroxidation. Archives of Biochemistry and Biophysics, 125(1), 189–198. https://doi.org/10.1016/0003-9861(68)90638-8

Jones, H.G (2014): Plants and Microclimate: A quantitative Approach to n Environmental Plant Physiology (3rd Edition). Cambridge University Press.

Sanchez Rodriguez, E., Romero, L., & Ruiz, J. M. (2016). Role of grafting in resistance to water stress in tomato plants: Ammonia production and assimilation. Journal of Plant Growth Regulation, 32(4), 831–842. https://doi.org/10.1007/s00344-016-9621-5

Sharma, P., Jha, A. B., Dubey, R. S., & Pessarakli, M. (2012). Reactive oxygen species, oxidative damage, and ant oxidative defense mechanism in plants under stressful conditions. Journal of Botany, 2012, 1–26. https://doi.org/10.1155/2012/217037

Steel, R. G. D., Torrie, J. H., & Dickey, D. A. (1997). Principles and procedures of statistics: A biometrical approach (3rd ed.). McGraw-Hill.

Taiz, L., Zeiger, E., Møller, I. M., & Murphy, A. (2018). Plant physiology and development (6th Ed.). Sinauer Associates.

Waheed, A., Hamid, F. S., Ahmad, S., Ahmad, M., Haider, G., & Danish, S. (2021). Influence of water deficit stress on oxidative stress markers and antioxidant defense in Capsicum annuum L. Physiology and Molecular Biology of Plants, 27(4), 881–892. https://doi.org/10.1007/s12298-021-00993-5

Appendix

Table 1. Soil physical and chemical properties at experimental site

Property	Value	Unit
Ph (H_20)	6.2	-
Organic Carbon	1.35	%
Total Nitrogen	0.12	%
Available Phosphorus	18.5	mg/kg
Exchangeable Potassium	0.32	cmol(+)/kg
Calcium	3.8	cmol(+)/kg
Magnesium	1.5	cmol(+)/kg
Cation Exchange Capacity	8.6	cmol(+)/kg
Soil Texture	Sandy loam	-
Soil moisture Storage (SMS)	185-210	mm
Water Holding Capacity (Whc)	0.28	cm/h
Bulk Density	1.42	g/cm^3
Porosity	46	%
Infiltration Rate	5.6	cm/h^{-1}

Table 2. Meteorological data for the 2022 growing season at Ado Ekiti

Month	Rainfall (mm)	Rainy Days	Mean Max Temp (°C)	Mean Min Temp (°C)	Relative Humidity (%)	Total Sunshine (hrs)
July	186	14	28.6	21.8	84	142
August	224	18	28.2	21.5	86	138
September	142	12	29.8	22.1	82	156
October	96	8	30.2	22.8	78	168
November	48	4	30.4	23.2	74	182
Total						
Average	696	56	29.4	22.3	80.4	786

Rainfall data represent the effective growing period June-November data

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Table 3: Functional and Yield Traits of Cayenne Pepper under Different Water Stress Levels

Treatment	Leaf Area (cm²)	Chlorophyll content Mg/g^{-1FW}	Days to Flowering	Fruit number	Fruit length (cm)	Fruit yield g/pot	Fruit yield t/ha
NS 100% FC	485.2^{a}	52.3^{b}	38^{c}	18.4^{a}	8.6^{a}	6.43^{a}	1.31
MS 60% FC	452.6^{a}	59.8^{a}	41^{b}	17.6^{a}	8.2^{a}	6.18^{a}	1.26
SS 40% FC	318.4^{b}	38.6^{c}	46^{a}	11.2^{b}	6.5^{b}	3.99^{b}	0.81
SD	88.09	10.75	4.04	3.95	1.12	1.34	0.28
SEM ±	50.86	6.20	2.33	2.28	0.64	0.78	0.16
CV (%)	21.04	21.39	9.70	25.09	14.37	24.30	24.4

Means within the same row followed by different superscript letters (a, b, c) are significantly different at $p \leq 0.05$ by Tukey's HSD test. NS = No Stress (100% FC); MS = Mild Water Stress (60% FC); SS = Severe Water Stress (40% FC). SD = Standard Deviation; SEM = Standard Error of Mean; CV% = Coefficient of Variation.

Table 4: Physiological and Biochemical Traits of Cayenne Pepper under Different Water Stress Levels

Treatment	Relative Water Content (%)	Soil Moisture Storage (%)	Crop Water Storage (m/Lplant)	Water Use Efficiency (kg/ m^{3})	Proline content (µmol/g FW)	MDA (nmol/g)	Antioxidant Activity (%)
NS (100% FC)	86.4	84.0^{a}	215.6^{a}	3.12^{b}	1.6^{c}	2.1^{c}	18.5^{c}
MS (60% FC)	74.8	50.4^{b}	198.4^{b}	4.85^{a}	4.3^{b}	3.5^{b}	27.6^{b}
SS (40% FC)	61.3	33.6^{c}	162.7^{c}	2.01^{c}	7.8^{a}	6.9^{a}	36.8^{a}
SD	12.55	25.53	26.95	1.43	3.11	2.47	9.15
SEM ±	7.24	14.74	15.56	0.83	1.79	1.42	5.28
CV (%)	16.92	45.60	14.01	43.00	62.02	59.20	33.11

Means within the same row followed by different superscript letters (a, b, c) are significantly different at $p \leq 0.05$ by Tukey's HSD test. NS = No Stress (100% FC); MS = Mild Water Stress (60% FC); SS = Severe Water Stress (40% FC). SD = Standard Deviation; SEM = Standard Error of Mean; CV% = Coefficient of Variation.

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Table 5: Summary Table of F-values, degrees of freedom, probability levels, and CV% for all measured traits of Cayenne pepper under three water stress levels (CRD, df Treatment = 2, df Error = 6)

Table	Trait/Parameters	F (2,6)	P-Value	Significance	CV (%)	WUE/Stress pattern
3	Leaf Area (cm^2)	**F(2,6)**	**P-value**	**Significance**	**CV (%)**	**WUE/Stress Pattern**
3	Chlorophyll Content	93.20	0.0000	**	3.97	NS > MS > SS
3	Days to flowering	307.86	0.0000	**	2.15	MS > NS > SS
3	Fruit number per plant	26.87	0.0010	**	2.88	NS < MS < SS (delay)
3	Fruit length (cm)	44.72	0.0002	**	6.61	NS = MS > SS
3	Fruit Yield (g/pot)	40.93	0.0003	**	4.46	NS = MS > SS
3	Fruit Yield (t/ha)	32.92	0.0006	**	7.45	NS = MS > SS
4	Soil Moisture Storage (%)	153.73	0.0000	**	3.64	NS = MS > SS
4	Crop Water Storage (Ml/plant)	372.84	0.0000	**	4.19	NS > MS > SS
4	WUE (kg/ m^3)	83.57	0.0000	**	3.15	NS > MS > SS
4	Proline Content (µmol/g FW)	729.54	0.0000	**	2.57	MS > NS > SS
4	MDA Content (nmol/g)	341.45	0.0000	**	6.59	NS < MS < SS
4	Antioxidant Activity (%)	391.12	0.0000	**	5.34	NS < MS < SS
4	F-Critical P=0.05,df 2, 6)	274.98	0.0000	**	3.30	NS < MS < SS
4	F-Critical P=0.01,df 2, 6)	5.14	0.05	Threshold	—	—
		10.92	0.01	Threshold	—	—

All F-values are computed with df = 2 (treatment) and df = 6 (error). ** = highly significant at $p \leq 0.01$