**INTRODUCTION**

Onion (*Allium cepa* L.) cultivation plays a crucial role in global agriculture, serving as a fundamental crop for food security and economic livelihoods in many regions worldwide (Ochar & Kim, 2023). This indispensable horticultural crop is distinguished by its unique morpho-physiological characteristic: the development of a storage bulb. This bulb formation stage is critical, as it serves as the primary harvested product, stores carbohydrates, regulates water use efficiency, and influences growth dynamics under varying environmental conditions (Wakchaure et al., 2018). Unlike many other crops, the onion bulb is a complex modified stem structure composed of concentric leaf bases that adaptively respond to environmental cues, including photoperiod and soil moisture availability. Such physiological traits—including the photoperiod sensitivity that controls bulb initiation—are uniquely pronounced in onions and differ fundamentally from crops lacking adaptive storage organs (Brewster, 2018). This physiological complexity introduces significant variation among onion varieties in terms of how they manage water stress, affecting critical yield components.

Soil moisture status critically influences onion physiological processes, including photosynthesis, stomatal conductance, and transpiration, impacting each variety’s water use strategy and overall growth. The onion’s particular dependency on soil moisture is heightened due to the bulb’s high-water content and rapid cellular expansion during the bulb enlargement phase (Wakchaure et al., 2021). Unique among many crops, the onion’s bulb development period requires timely irrigation management, as both water deficit and excess irrigation can induce physiological stress that alters bulb size distribution, pungency, alliinase activity, and storability (Leskovar et al., 2012). Excess water may reduce bulb quality through increased disease incidence and nutrient leaching, while deficits often lead to reduced bulb size and increased bolting tendencies. Such impacts are not only agronomic but directly affect post-harvest shelf life and market acceptance, emphasizing the critical importance of tailoring irrigation regimes to varietal water sensitivities (Kwon et al., 2016).

Despite the agricultural importance of onions, the physiological responses of diverse onion varieties to soil moisture stress and irrigation management remain insufficiently characterized (Enciso et al., 2009). Ambiguity persists in the precise quantification and understanding of how differing levels of soil moisture tension affect these physiological attributes across onion varieties with varying tolerance to water stress. The complex interactions between soil moisture, soil temperature, and plant physiological responses demand detailed elucidation to enable optimized agronomic practices tailored to specific cultivars.

Prior investigations have documented the fundamental principles governing soil-plant water relationships, often highlighting the detrimental effects of water deficit on crop productivity through mechanisms such as reduced stomatal aperture, impairment of photosynthetic machinery, and altered transpiration (Wakchaure et al., 2021). Yet, many of these reports concentrate on general crop groups or single varieties under limited experimental conditions, falling short of comprehensive comparative analyses that incorporate varietal differentiation and multiple irrigation regimes with precise SWP measurements (Sarkar et al., 2008). The variability in onion genotypes regarding drought sensitivity further complicates the application of a uniform irrigation management protocol (Gedam et al., 2021). The absence of granular data on physiological responses to precise soil moisture tensions has left a substantial gap in understanding cultivar-specific irrigation thresholds and their effects on plant development and yield components. Additionally, the potential modulation of soil temperature by soil moisture status and its subsequent effect on physiological processes remains underexplored in different irrigation contexts and onion genotypes (Bachie et al., 2019).

Varietal differences within onions are striking, reflecting complex genetic adaptations to moisture regimes and temperature thresholds that regulate bulb development. Onion cultivars exhibit distinct phenological profiles absent in non-bulbing crops; these include discrete timing of bulb initiation, susceptibility to soil moisture stress during critical growth phases, and differing ratios of bulb size categories (Wakchaure et al., 2021). The patterns of bulb size distribution influence both yield and quality metrics uniquely in onions, where market prices are heavily influenced by bulb uniformity and size class proportions, unlike grain or leafy crops where yield components are fundamentally different (Leskovar et al., 2012). Additionally, the bulb’s role as a carbohydrate reservoir interlinks with leaf area development, photosynthesis rate decline, and stomatal conductance fluctuations—phenomena tightly regulated in onions and exhibiting cultivar-specific responses to irrigation schedules (Wakchaure et al., 2018).

The physiological underpinning of these varietal responses centers on the onion’s sensitivity to soil moisture tensions and temperature fluctuations, which modulate gas exchange and osmotic adjustments. Onions uniquely modulate stomatal aperture to balance carbon assimilation with water loss during bulb expansion stages, a trait not as critically timed or expressed in other horticultural crops lacking a storage bulb (Bachie et al., 2019). The dynamic interplay between transpiration rates and photosynthetic capacity across moisture treatments influences not only immediate biomass accumulation but also the biosynthesis of sulfur-containing compounds responsible for pungency and flavor, characteristics highly specific to onions (Gao et al., 2020). The production of these metabolites is often disrupted under inappropriate irrigation practices, affecting quality parameters that cannot be measured or mirrored in other crop species (Wakchaure et al., 2018). Such biochemical pathways make onion irrigation management more complex, as water stress influences both yield quantity and key sensory qualities distinct to this crop.

SWP measurement tools facilitate precise monitoring of soil moisture dynamics, enabling the accurate quantification of moisture gradients (Wayangkau et al., 2020). This detailed sensor data is critical, given the variable water requirements and stress thresholds observed among onion cultivars. For instance, Mata Hari maintains photosynthetic and stomatal function more effectively under moderate soil tension (Nunes et al., 2014), whereas onion varieties demonstrate contrasting water stress responses, underscoring the importance of genotype-specific irrigation schedules (Gedam et al., 2021). These varietal disparities directly influence key yield determinants such as bulb dry matter content, the proportion of large, and single-center bulbs(Feibert et al., 2022).

Soil temperature also plays a pivotal role in regulating onion bulb formation and maturation—an interplay particularly characteristic of bulbing crops (Ikeda et al., 2019). Elevated or fluctuating soil temperatures accelerate or delay bulb initiation by modulating enzymatic activities involved in carbohydrate metabolism, with varietal thresholds determining tolerance to thermal extremes (Sharma & Lee, 2016). Unlike in crops whose phenology depends primarily on above-ground temperature or photoperiod, onion bulb induction responds strongly to soil temperature regimes interacting with moisture status in a feedback loop affecting water uptake and physiological function (Mpanza, 2017). These interdependencies influence not only crop development timelines but also postharvest shelf life and market quality, underscoring the need for integrated soil moisture and temperature monitoring.

Yield parameters in onions are uniquely stratified into distinct bulb size classes—large weight (LW), jumbo weight (JW), and colossal weight (CW)bulbs—which respond differentially to soil moisture stress (Wakchaure et al., 2021). This categorization is a hallmark of onion production, setting it apart from other vegetable crops where yield is commonly expressed as total biomass or fruit number. The size classes are directly tied to market preferences and economic value, with environmental stressors and varietal genetic factors shaping their distribution. Water stress episodes during critical phenological windows often shift this distribution toward smaller, less commercially desirable bulb sizes (Leskovar et al., 2012). Accurate irrigation management tailored to varietal water sensitivity can mitigate these effects, promoting yield uniformity and maximizing returns.

Leaf area index (LAI) progression throughout the onion growth cycle further defines varietal differences in water use efficiency, a significant factor since leaf canopy development supports photosynthetic activity essential for bulb filling (Wakchaure et al., 2021). Some onion varieties display gradual LAI increases compatible with sustained photosynthesis during the bulb expansion phase, whereas abrupt LAI changes, as observed in other varieties, may signal physiological stress and growth trade-offs (Ballesteros et al., 2018). This relationship between canopy dynamics and storage organ development typifies onion crop physiology and warrants specialized attention in irrigation scheduling.

**The novelty of our study lies in analyzing the bulb stage of three onion varieties using two sensor types across six soil moisture tension treatments.** Addressing these gaps in onion-variety-specific physiological responses to varying soil moisture and temperature conditions requires the integration of sensor technologies. Recent advances in soil moisture monitoring tools combined with precise gas exchange measurements, afford an unprecedented view of the soil-plant-atmosphere continuum unique to onion cultivation (Rahman et al., 2024). Such comprehensive approaches facilitate the development of irrigation schedules precisely aligned with the physiological stages of bulb initiation, enlargement, and maturation. This targeted management enhances water use efficiency and crop resilience, critical for sustainable production amid climate-related uncertainties (Wakchaure et al., 2021).

**MATERIALS AND METHODS**

The onion irrigation scheduling trial was conducted under field conditions with drip irrigation at Texas A&M AgriLife Research and Extension Center at Uvalde during the 2023-2024 growing season. The soil type is silty clay loam with 29% sand, 23% silt and 48% clay. The trial was seeded at seeding density of 2 inches and four rows per bed (top of bed width was 24”) on November 7, 2023, on parallel beds, with each bed size 1.0 m by 6.1 m. The experiment was laid out in a split-plot (main plot – variety, sub-plot - irrigation schedule) design with four replications. For the irrigation schedule, we followed five levels of soil water potential −25 kPa, −50 kPa, −75 kPa, −100 kPa, −125 kPa with TEROS 21 solid matrix potential sensors, and a control, −50 kPa with Watermark granular matrix sensors, all installed at 20-cm depth. The soil sensors were installed on December 11-12, 2023. To ensure good contact between soil and the sensor during the wetting and drying cycles, each sensor was packed with a layer of fully saturated soil to form a ball of approximately 8-cm diameter and are fully lower to the 20-cm depth in a pre-made hole with slightly larger diameter. Then, the gap between the mud ball and the original soil was sealed by thick soil and water mixture type fluid. Data of the Teros-21 sensors were recorded using EM-50 dataloggers (METER Group) and the data for the watermark sensors were recorded using AM-400 dataloggers (Henson Company). Irrigation scheduling started shortly before the start of the bulb enlargement stage, roughly from 03/01/2024 and continued on 04/30/2024. The irrigation for each treatment was applied when the matric potential was lower than the target threshold and each bed was managed separately, considering the potential differences in water depletion among three onion varieties.

Standard agronomic, pest, and fungicide practices for onions were followed. Meteorological and ETc data from the Uvalde Center were recorded. Data of leaf area index and canopy cover were measured using an LP-80 Ceptometer (Meter Group). Onions were harvested by hand on May 20, 2024. On the same day of harvest, bulbs were graded (small = <50 mm diameter, medium = 50 to 75 mm, jumbo = 75 to 100 mm, colossal = >100 mm), and onions in each class were counted and weighed separately. A subset of the samples, ten bulbs, was evaluated for single centeredness by cutting the onions in halves and counting the number of rings. A mixed model split-plot analysis of variance was conducted with variety and irrigation schedule as a fixed effect and replications being a random effect. For instances in which differences among treatments exist, a mean separation test was utilized to determine which means are different.

**RESULTS**

**Soil Temperature, °C**

across treatment

Soil temperature showed similar trends across treatments and dates (**Figure 1**). There were not many differences between the soil temperature (+1 °C) among different treatments. It was expected that high tension treatments (-125 kPa) may show slightly higher soil temperatures compared to lower tension treatments (-25 kPa) which is not proved in our study.

across date

On 03/01/2024, the temperature was low across all the treatments, which rose a little 03/06/2024 and plunged again. This up-down trend kept on until 03/18/2024, after which the temperature kept on increasing in all treatments. The highest was recorded as 26.30 °C in -75 kPa on 04/30/2024 with +1 °C differences in other treatments.

**Figure 1**. Temporal dynamics of soil temperature (°C) under different soil water tension treatments (-25 kPa, -50 kPa, -75 kPa, -100 kPa, and -125 kPa) recorded from March 1 to April 30, 2024, during the onion growing season at the Texas A&M AgriLife Research and Extension Center, Uvalde, Texas.

**Soil Moisture as VWC,** **m3 m-3**

volumetric water content = VWC

across treatment

The trend across treatments showed that -125 kPa had the highest VWC, followed by -100 kPa, ranging from 0.33-0.39 m3 m-3 and 0.34-0.37 m3 m-3, respectively (**Figure 2**). The treatment -25 kPa and -50 kPa showed VWC ranging from 0.29-0.32 m3 m-3, and 0.29-0.33 m3 m-3, respectively. The treatment -75 kPa showed the lowest VWC ranging from 0.25-0.27 m3 m-3.

across date

The VWC trend on different dates was nearly similar. On 03/04/2024, the VSC was higher, which kept on lowering until 03/31/2024. It slightly increased on the next day and decreased again. The highest VWC was found on 04/18/2024 which later decreased slightly.

**Figure 2**. VWC measured throughout the onion growing season under soil water tension treatments (-25 kPa, -50 kPa, -75 kPa, -100 kPa, and -125 kPa) at the Texas A&M AgriLife Research and Extension Center, Uvalde, Texas. Data represents daily VWC values collected from sensor-based monitoring systems during the 2024 onion cropping period.

**SWP, kPa**

soil water potential = swp

across varieties

SWP was generally low in Mata Hari (**Figure 3B**), followed by Hornet (**Figure 3A**) and high in Amadea (**Figure 3C**). Mata Hari experienced a high number of days with low SWP (-19.48 to -47.36 kPa), indicating relatively higher water availability while Hornet (-18.96 to -42.03 kPa) and Amadea (-18.34 to -45.07 kPa) had higher water stress, respectively. Mata Hari was slightly better in keeping the lower SWP while Amadea showed highest fluctuations.

across treatments

The SWP rapidly increased as the tension of the treatment increased. The -125 kPa and -100 kPa treatments recorded the lowest (most negative) SWP, reflecting drier soil conditions. The -25 kPa and -50 kPa treatments showed higher water availability. The treatment -50 kPa (WM) showed different SWP values than the MP-6, with medium SWP and moderate stress (-20.67 to -80.33 kPa).

across dates

On specific dates, SWP values were less negative (03/01/2024 - 03/13/2024), indicating higher soil moisture levels. By 03/20/2024, SWP values became more negative, reflecting increased water stress. The driest conditions were observed between 04/20/2024 - 04/30/2024.

**Figure 3**. Time series analysis of SWP in Hornet (**A**), Mata Hari (**B**) and Amadea (**C**) hybrids under different soil moisture tension treatments (-25 kPa, -50 kPa, -50 kPa (WM), -75 kPa, -100 kPa, and -125 kPa) from March 1 to April 30, 2024.

**Gas Exchanges and Physiological Parameters, mmol m-2 s-1**

Gas exchange parameters (photosynthesis, stomatal conductance, and transpiration) varied across dates, varieties, and treatments.

**Photosynthesis**

across dates

Photosynthesis at the initial dates were high and kept on decreasing as the growing season progressed. High levels of photosynthesis were recorded from 03/02/2024 - 03/10/2024 with highest value as 26.45 (mmol m-2 s-1) after which, it started to decrease (**Figures 4A – 4C**). The date 03/26/2024 showed low levels of photosynthesis with lowest value as 6.66 (mmol m-2 s-1). The date 04/21/2024 showed slight progress with some moderate levels of photosynthesis.

across variety

Mata Hari provided the highest values and a high number of days with better levels of photosynthesis. The trend was mostly higher than 22 (mmol m-2 s-1) while only once came down to 9.53 (mmol m-2 s-1). Amadea recorded medium levels of photosynthesis with high fluctuations. It also dipped to the same level (9.84 mmol m-2 s-1). While Hornet showed low photosynthetic values with less fluctuations and with higher stressed values ranging from 11.57-20.91 (mmol m-2 s-1).

across treatments

The treatments -25 kPa, -50 kPa and -50 kPa (WM) showed higher photosynthesis. The trend in these treatments was almost similar, which started from higher photosynthesis and slightly decreased. For -75 kPa, -100 kPa and -125 kPa, they followed a similar trend but with lower photosynthetic values and less fluctuation.

**stomatal conductance**

across dates

The stomatal conductance on 03/02/2024 and 03/10/2024 showed higher values (0.48-1.40 mmol m-2 s-1), as shown in **Figures 4D – 4F**. These values started to decrease as the seasons progressed. A rapid plunge was recorded on 03/26/2024 and 04/07/2024. The drop was recovered on 04/21/2024 with values ranging from 0.13-1.33 mmol m-2 s-1.

across variety

Mata Hari showed high stomatal conductance, followed by Amadea and Hornet. There was high fluctuation in Mata Hari with values (0.21-1.37 mmol m-2 s-1). Hornet also showed high fluctuation but with low values (0.17-0.84 mmol m-2 s-1). Amadea showed high stability with medium values (0.13-0.93 mmol m-2 s-1).

across treatments

The treatments -25 kPa and -50 kPa recorded high stomatal conductance. As the treatments tension increases, the fluctuation increases while conductance decreases. Lowest conductance was recorded in -125 kPa, -50 kPa (WM), and -75 kPa treatments.

**transpiration**

across dates

The start of the growing season showed higher transpiration. On 03/02/2024, the transpiration was highest (10.73 mmol m-2 s-1), as shown in **Figures 4G – 4I**. A sudden decrease was recorded on 03/10/2024 and 03/26/2024 with transpiration reaching up to (2.07 mmol m-2 s-1). The initial recovery was recorded on 04/07/2025 (3.37 mmol m-2 s-1) while the secondary recovery on 04/21/2024 stabilized the transpiration to normal (9.84 mmol m-2 s-1).

across variety

The highest transpiration was recorded in Mata Hari, followed by Amadea and low in Hornet with highest values as 10.59, 9.22 and 9.13 mmol m-2 s-1, respectively. Mata Hari, Amadea and Hornet ranged from 4.08-10.59 mmol m-2 s-1, 2.76-9.22 mmol m-2 s-1, and 3.27-9.13 mmol m-2 s-1, respectively. There were high fluctuations and trends across varieties were different.

across treatments

The high transpiration (along with better stability) was recorded in treatments -100 kPa and -125 kPa with values ranging from 5.89-9.87 mmol m-2 s-1 and 5.30-9.26 mmol m-2 s-1. The treatments -25 kPa, -50 kPa, -50 kPa (WM) and -75 kPa initially recorded higher transpiration which suddenly dropped.

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**Figure 4**. Photosynthetic rate (**A, B, C**, mmol), stomatal conductance (**D, E, F**, mmol), and transpiration rate (**G, H, I**, mmol) of three onion cultivars—Amadea, Hornet, and Mata Hari—measured under soil water tension treatments (-25 kPa, -50 kPa, -50 kPa (WM), -75 kPa, -100 kPa, and -125 kPa) from Mar 01 to Apr 30, 2024, during the onion growing season at the Texas A&M AgriLife Research and Extension Center, Uvalde, TX.

**Yield and Yield Parameters**

large weight = LW

jumbo weight = JW

single center = SC

Our study categorized yield (adjusted, kg ha-1) as low, medium and high. **In -25 kPa**, the **yield** was high in Hornet (217,772.61 kg ha-1), followed by Amadea (156,520.14 kg ha-1), and low in Mata Hari (123,498.76 kg ha-1), as shown in **Figures 5A – 5C and Table 1**. Amadea was expected to provide a low **yield** due to experiencing high stress. However, Mata Hari resulted in providing low yield despite experiencing low soil moisture stress. Mata Hari experienced high while Hornet experienced low number of **soil moisture stress days**, respectively. This shows that providing excess amounts of irrigation to Mata Hari does not benefit. **LW** of onions was high in Hornet, followed by Mata Hari and Amadea, while **JW** was high in Hornet, followed by Amadea. **SC** onions were highest in Amadea (95%), followed by Mata Hari (44%) and Hornet (35%). Amadea showed strong coefficient of determination (R2 = 0.87) followed by Mata Hari (R2 = 0.86).

**In -50 kPa**, the high **yield** was produced by Amadea (214,130.31 kg ha-1), followed by Hornet (125,000.01 kg ha-1) and Mata Hari (88,973.79 kg ha-1). Amadea experienced high while Hornet experienced low number of soil moisture stress days. Mata Hari cannot withstand any soil moisture stress. The highest percentage of **LW** onions was found in Amadea, followed by Hornet and Mata Hari, while the percentage of **JW** was found in Amadea only. The highest **SC** percentage was found in Hornet, followed by Amadea and Mata Hari. Coefficient of determination was highest in Mata Hari, Hornet and Amadea as R2 = 0.90, 0.78 and 0.76, respectively.

**In -75 kPa**, the number of soil moisture stress days among varieties were nearly similar but the intensity was different. High **yield** was provided by Amadea, followed by Hornet and Mata Hari. Mata Hari experienced medium while Hornet experienced high number of soil moisture stress days. The **LW** was highest in Amadea, followed by Hornet and Mata Hari with 54%, 38% and 25%, respectively. **JW** was only found in Amadea with 16%, while **SC** was highest in Hornet, followed by Amadea and Mata Hari. Strong model determination was shown by Amadea, followed by Mata Hari and Hornet with R2 = 0.91, 0.86, 0.67, respectively. The model variation in Mata Hari despite its low yield was influenced by the low intensity of soil moisture stress.

**In -100 kPa**, Hornet provided the highest **yield** while experiencing high intensity of soil moisture stress. Amadea experienced the highest number of soil moisture stress days and provided medium yield, while Mata Hari provided low yield while experiencing the lowest number of soil moisture stress days. The **LW** was highest in Hornet, followed by Amadea and low in Mata Hari, while **JW** was only available in Hornet. The **SC** was provided highest in Amadea, followed by Mata Hari and low in Hornet with 90%, 72% and 27%, respectively. The R2 values for Amadea, Hornet and Mata Hari show 0.94, 0.73 and 0.53, respectively.

In **-125 kPa**, Hornet provided the highest **yield** (171,880.06 kg ha-1) while experiencing the most intense soil moisture stress (**Figures 5A – 5C**). Amadea provided medium yield (116,002.64 kg ha-1) while experiencing moderate but longer stress duration. Mata Hari provided low yield (112,065.32 kg ha-1) while experiencing mild soil moisture stress. The coefficient of determinationfor Mata Hari showed (R2 = 0.87), Hornet as (R2 = 0.72), and Amadea as (R2 = 0.53).

In **-50 kPa (WM)**, the highest soil moisture stress began on 03/24/2024 and lasted until 04/19/2024, slightly earlier and shorter than the MP-6 treatments. Hornet, with moderate stress, yielded highest (195,887.95 kg ha-1) due to good adaptive traits under drying period. Mata Hari, with medium stress, yielded moderate (142,670.79 kg ha-1) due to its sensitivity to short-term soil moisture deficits. Amadea, with prolonged stress, yielded lowest (141,523.92 kg ha-1). The model showed the strongest predictive relationship in Mata Hari, followed by Hornet and low in Amadea with R2 values as 0.70, 0.67 and 0.25, respectively, indicating that the weaker relationship in Amadea may reflect cultivar-specific traits such as effect on root system or delayed bulb growth under soil moisture stress.

**Figure 5**. Impact of SWP thresholds on yield and yield parameters of three onion cultivars (Hornet [**A**], Mata Hari [**B**], and Amadea [**C**]) in Uvalde, Texas, during the 2024 spring growing season (March 1 - April 31).

**Table 1.** ANOVA, LSD and mean comparison of yield and bulb quality for three onion varieties (Hornet, Mata Hari, and Amadea) under six soil water tension treatments (-25 kPa, -50 kPa, -50 kPa [WM], -75 kPa, -100 kPa, and -125 kPa) during the onion growing season from March 1 to April 30, 2024, in Uvalde, Texas.

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| **Treatment numbers** | **Treatments** | **Varieties** | **Yield (adjusted, kg ha-1)** | **SWP (kPa)** | **No. of bulbs (ha-1)** | **Small bulbs weight (%)** | **Small bulbs number (%)** | **Medium bulbs weight (%)** | **Medium bulbs number (%)** | **Large bulbs weight (%)** | **Large bulbs number (%)** | **Jumbo bulbs weight (%)** | **Jumbo bulbs number (%)** | **Single center (%)** |
| **T1** | **-25 kPa** | **Hornet** | 217772.61 | -24.07 | 217772.61 | 4.85 | 13.33 | 19.29 | 26.37 | 61.30 | 52.38 | 14.56 | 7.91 | 35.00 |
| **Mata Hari** | 123498.76 | -19.24 | 123498.76 | 21.06 | 41.11 | 27.68 | 29.11 | 51.25 | 29.78 | 0.00 | 0.00 | 44.17 |
| **Amadea** | 156520.14 | -34.83 | 156520.14 | 15.26 | 29.67 | 39.86 | 39.21 | 36.42 | 26.11 | 8.45 | 5.00 | 95.00 |
| **T2** | **-50 kPa** | **Amadea** | 125000.01 | -58.22 | 156180.87 | 7.53 | 18.98 | 24.07 | 32.66 | 51.43 | 39.33 | 16.97 | 9.04 | 70.00 |
| **Mata Hari** | 88973.79 | -50.84 | 108368.75 | 24.82 | 45.08 | 49.90 | 39.88 | 25.28 | 15.04 | 0.00 | 0.00 | 47.50 |
| **Hornet** | 214130.31 | -57.78 | 183058.83 | 9.80 | 18.68 | 51.23 | 50.89 | 38.96 | 30.43 | 0.00 | 0.00 | 97.50 |
| **T3** | **-50 kPa WM** | **Hornet** | 195887.95 | -35.01 | 195887.95 | 4.02 | 13.38 | 17.08 | 25.68 | 57.33 | 49.40 | 21.57 | 11.54 | 40.00 |
| **Mata Hari** | 142670.79 | -47.43 | 142670.79 | 43.36 | 62.73 | 39.86 | 28.97 | 16.78 | 8.30 | 0.00 | 0.00 | 69.44 |
| **Amadea** | 141523.92 | -39.90 | 141523.92 | 15.56 | 34.29 | 50.87 | 46.39 | 33.57 | 19.33 | 0.00 | 0.00 | 92.50 |
| **T4** | **-75 kPa** | **Amadea** | 156180.87 | -89.52 | 125000.01 | 5.93 | 17.73 | 21.58 | 27.35 | 54.48 | 43.76 | 18.00 | 11.16 | 60.00 |
| **Mata Hari** | 108368.75 | -69.90 | 88973.79 | 17.29 | 27.44 | 47.81 | 50.15 | 34.90 | 22.41 | 0.00 | 0.00 | 40.00 |
| **Hornet** | 183058.83 | -59.27 | 214130.31 | 12.06 | 23.74 | 51.66 | 52.27 | 36.28 | 23.99 | 0.00 | 0.00 | 95.00 |
| **T5** | **-100 kPa** | **Hornet** | 185098.37 | -103.04 | 185098.37 | 6.53 | 16.80 | 17.36 | 23.09 | 45.63 | 41.25 | 30.48 | 17.94 | 27.50 |
| **Mata Hari** | 75331.01 | -45.79 | 75331.01 | 45.41 | 65.69 | 50.31 | 32.31 | 4.28 | 2.00 | 0.00 | 0.00 | 72.50 |
| **Amadea** | 121040.28 | -76.30 | 121040.28 | 22.22 | 37.64 | 53.83 | 47.14 | 23.96 | 15.22 | 0.00 | 0.00 | 90.00 |
| **T6** | **-125 kPa** | **Amadea** | 116002.64 | -86.30 | 116002.64 | 6.90 | 19.84 | 27.11 | 35.58 | 35.23 | 28.15 | 30.76 | 16.43 | 37.50 |
| **Mata Hari** | 95470.35 | -66.65 | 95470.35 | 28.56 | 48.93 | 54.49 | 43.50 | 16.95 | 7.57 | 0.00 | 0.00 | 50.00 |
| **Hornet** | 171880.06 | -96.17 | 171880.06 | 23.22 | 37.62 | 60.71 | 52.78 | 16.07 | 9.59 | 0.00 | 0.00 | 100.00 |
| ***P-values for Treatments / Varieties (α = 0.10)*** | | | *0.05 \*\* / 0.00 \*\** | *0.00 \*\* / 0.22* | *0.46 / 0.00 \*\** | *0.40 / 0.00 \*\** | *0.84 / 0.60* | *0.65 / 0.90* | *0.19 / 0.09 \*\** | *0.44 / 0.05 \*\** | *0.99 / 0.21* | *0.99 / 0.21* | *0.99 / 0.53* | *0.05 \*\* / 0.00 \*\** |
| ***LSD Treatments / Varieties*** | | | *a / c* | *b / a* | *a / a* | *a / b* | *a / b* | *a / a* | *a / a* | *a / a* | *a / b* | *a / a* | *a / a* | *a / a* |

*\* Letters with star within the rows indicate significant differences at α = 0.10, according to LSD test.*

**LAI**

across date

LAI values were lowest at the start of the growing season on 02/23/2024, averaging around 0.2. Slight fluctuations were observed on 03/01/2024, but overall values remained low. A noticeable increase began by 03/16/2024, with medium LAI ranging from 0.22 to 0.48. A sharp rise was observed on 03/27/2024, when the highest LAI of 1.42 was recorded. On 04/07/2024, values remained high but slightly declined compared to the previous date, with the highest LAI as 1.31 and some lower values appearing.

across variety

Amadea showed higher LAI values, followed by Hornet and Mata Hari (**Figures 6A, 6B, 6C**). Amadea exhibited a gradual increase from low (0.16-0.23) to medium (0.3-0.52) and then to high LAI values (0.65-1.42). Hornet followed a similar trend but with a shorter duration in the medium range. Mata Hari displayed an abrupt shift from low to medium and high LAI values, a pattern observed only in this variety.

across treatment

All treatments showed gradual increases, however, the highest LAI (1.02-1.42) was observed in 50 kPa, 50 kPa (WM) and 75 kPa. These treatments supported steady canopy development. The 100 kPa and 125 kPa treatments maintained moderate LAI (0.65-1.09) indicating reasonable growth under higher soil moisture stress. The 25 kPa treatment showed lower LAI (below 0.8) with limited progression, reflecting suboptimal conditions for canopy expansion.

**Figure 6**. SWP and LAI trends in three onion varieties (Hornet [**A**], Mata Hari [**B**] and Amadea [**C**]) under soil water tension treatments (-25 kPa, -50 kPa, -50 kPa (WM), -75 kPa, -100 kPa, and -125 kPa) from Mar 01 to Apr 30, 2024, spring season in Uvalde, Texas.

**DISCUSSION**

**Predicting SWP**

Our study predicted the SWP using multiple linear regression modeling in R statistical package. The model was calibrated and evaluated several times to provide realistic and practical values. ET and the quantity of irrigation provided in fields were kept as base factors for this prediction in statistical modeling. Ortola (2013) simulated the SWP in onions and found high variability with high yield on sandy soils and ow yield on sandy loam soils.

**Evapotranspiration**

Prediction of SWP was performed using the weather data from the NASA Power LARC was analyzed, however, the study of Leskovar et al., (2012) has shown that local data (sensor, ET among others) are more accurate in predicting the SWP. Therefore,LICOR based LAI data was used to estimate the ET values, however, the values significantly fluctuated. Al-Gaadi et al., (2022) tested two center-pivot irrigation systems and retrieved data from Landsat-8 to estimate onion evapotranspiration (ETa) with some bias values. Our study tested the potential evapotranspiration (PET) acquired from the local weather meter, which was first changed into cumulative ET, by adding up all the ET values from the first irrigation event till the next irrigation event and used for prediction. The predicted SWP resulted in higher values when compared with the observed SWP. Hence, the number of plants, the planting density of onions, volumetric water content (cm-3 cm-3), and the local crop coefficient (Kc) were then added for actual evapotranspiration (ETa) for further accuracy of the prediction (**Figure 7A**). The SWP in **Figure 7A** was dependent on rainfall and irrigation regimes as shown in **Figure 7B**. This helped support the balance of those treatments which provided non-accurate data due to weather changes. Such as the values for the treatment -75 kPa showed high fluctuations, while the accurate prediction supported the values of -75 kPa in different days of irrigation. Bachie et al., (2019) studied the same experiences where the photosynthetic rates and stomatal conductance of several of their onion varieties acted differently, ultimately affecting ETa. The scenario in our study has been highlighted in **Table 2** where the corresponding SWP is shown in the field capacity for the Uvalde clay soil.

**Table 2.** Soil water characteristics for Uvalde, Texas clay soil.

|  |  |  |
| --- | --- | --- |
| **Soil water potential (kPa)** | **Volumetric water content (v/v, cm-3 cm-3)** | **Comments** |
| -1 | 0.47 |  |
| -2 | 0.46 |  |
| -3 | 0.45 |  |
| -5 | 0.43 |  |
| -10 | 0.39 |  |
| **-20** | **0.35** | **Field capacity (repacked clay soil)** |
| -30 | 0.33 |  |
| -40 | 0.31 |  |
| -50 | 0.30 |  |
| -60 | 0.29 |  |
| -70 | 0.28 |  |
| -80 | 0.28 |  |
| -90 | 0.27 |  |
| **-100** | **0.27** | **Refill point** |
| -200 | 0.24 |  |
| -500 | 0.21 |  |
| -1000 | 0.19 |  |
| **-1500** | **0.18** | **Permanent wilting point** |

A graph showing different colored lines

AI-generated content may be incorrect.

**Figure 7**. (**A**) Treatment -75 kPa is compared among tested onion varieties while the yield (adjusted, kg ha-1) of each variety is shown in red square (Hornet), green circle (MataHari) and blue triangle (Amadea); (**B**) irrigation and rainfall regimes shown for each variety (Amadea, Hornet and MataHari) while up-arrow shows the availability of the ET and circles show the non-availability of the ET.

**Varietal Effects**

**Table 3** illustrates the seasonal irrigation schedule for three tested onion varieties, while **Table 4** presents the cumulative ET that transforms into PET over time during the onion growing season. As shown, the Hornet variety needed irrigation in a short period of time, since a high SWP (kPa) was found in the Hornet. While MataHari and Amadea showed the need for irrigation at almost similar and later days than Hornet. This affected the growth of MataHari in a significant way which further designated the varieties into early, mid-early and late (**Table 5**). Enciso et al., (2009) obtained higher yields when they kept the SWP above -30 kPa. However, their yield was significantly affected when the SWP increased from -50 kPa.

**Table 3.** Irrigation needs for three onion genotypes at different growth periods.

|  |  |
| --- | --- |
| **Genotypes** | **Irrigation events** |
| Hornet | \*---------------------------\*----------------------------------------------------------- |
| Mata Hari | \*------------------------------------------------\*-------------------------------------- |
| Amadea | \*------------------------------------------------\*-------------------------------------- |

**Table 4.** Cumulative (ETa) using the potential evapotranspiration (PET).

|  |  |  |
| --- | --- | --- |
| **Days** | **Evapotranspiration** | **∑ET** |
| D1 | ET1 | ET1 |
| D2 | ET2 | ET1 + ET2 |
| D3 | ET3 | ET1 + ET2 + ET3 |
| D4 | ET4 | ET1 + ET2 + ET3 + ET4 |
| D5 | ET5 | ET1 + ET2 + ET3 + ET4 + ET5 |
| Dn | ETn | ET1 + ET2 + ET3 + ET4 + ET5 + ETn |

**Table 5**. Summary of Soil-Plant-Water Interactions and Physiological Responses across onion varieties and treatments.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Varieties** | **SWP (kPa)** | **Photosynthesis (mmol m-1 s-1)** | **Stomatal conductance (mmol m-1 s-1)** | **Transpiration (mmol m-1 s-1)** | **Classification** |
| Mata Hari | −19.48 to −47.36 | 22–26.45 (highest, stable) | 0.21–1.37 (high, early) | 4.08–10.59 | Early |
| Amadea | −18.34 to −45.07 | 9.84–25 (moderate, unstable) | 0.13–0.93 (moderate, stable) | 2.76–9.22 | Mid-Early |
| Hornet | −18.96 to −42.03 | 11.57–20.91 (low, stable) | 0.17–0.84 (low, stable) | 3.27–9.13 | Late |

**CONCLUSION**

Our study showed significant differences in early, mid-early and late onion varieties. Mata Hari, Amadea, and Hornet showed to be early, mid-early and late varieties, respectively. The relationship between final yield and its components with SWP during the 74-day growing period after bulb initiation showed a strong negative correlation, indicating that more negative SWP values were associated with reduced bulb yield, leaf area, and physiological parameters such as stomatal conductance and photosynthetic rate. This suggests that yield components (such as bulb diameter, dry matter, and total biomass) declined as SWP became more negative. SWP was a reliable indicator of plant water stress and significantly influenced both growth dynamics and physiological processes. Optimal yield was associated with moderate to less negative SWP values.

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