

# Influence of differential watering regimes on physiological performance and productivity of *Vachellia tortilis*, *Vachellia nilotica*, and *Senegalia senegal* in the Semi-Arid Zone of Maiduguri, Nigeria

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Received 26th October 2025; Accepted 23rd December 2025

**ABSTRACT:** Water stress is a major constraint on plant productivity in semi-arid regions of Sub-Saharan Africa. This study examined the physiological responses and productivity of three leguminous species, *Vachellia tortilis*, *Vachellia nilotica*, and *Senegalia senegal*, under differential watering regimes in the semi-arid zone of Maiduguri, Nigeria. Seedlings were subjected to four treatments: M0 (control; watered four times per week), M1 (slight moisture stress), M2 (moderate stress), and M3 (severe stress). Relative water content (RWC), plant water deficit (PWD), chlorophyll pigments, total dry matter accumulation (TDM), and net primary productivity (NPP) were measured at 60, 90, and 120 days. Results showed that *V. tortilis* and *S. senegal* maintained high RWC and exhibited adaptive increases in NPP under moderate stress, while *V. nilotica* produced the highest biomass under optimal moisture but experienced significant reductions in NPP and pigment content under severe drought. Chlorophyll stability improved under moderate stress in *V. nilotica* and *V. tortilis*, whereas *S. senegal* was more sensitive to severe moisture deficits. Correlation analysis revealed strong negative relationships between NPP and watering regimes, particularly in *V. nilotica*. The study highlights species-specific drought responses: *V. tortilis* and *S. senegal* demonstrated greater physiological plasticity under moderate water stress, whereas *V. nilotica* was more productive under favourable conditions but less tolerant to prolonged drought. These findings support the suitability of *V. tortilis* and *S. senegal* for dryland afforestation and ecological restoration, and emphasise the usefulness of NPP as a quantitative indicator for selecting drought-resilient species under climate variability in West African drylands.

**Keywords:** Drought stress, physiological adaptation, relative water content, net primary productivity, *Vachellia*, *Senegalia*, dryland forestry, Nigeria.

## INTRODUCTION

Water availability is a primary determinant of plant growth and productivity in arid and semi-arid regions. As climate variability intensifies across Sub-Saharan Africa, including the semi-arid northeastern zone of Nigeria, the sustainability of forest and agroforestry systems increasingly depends on the drought resilience of key species (IPCC, 2022; Uni *et al.*, 2023). Understanding how native species respond physiologically to soil moisture

deficits is therefore essential for identifying drought-resilient candidates suitable for reforestation, afforestation, and land restoration programmes (Haile *et al.*, 2021; Zeleke *et al.*, 2021).

Species of *Vachellia* and *Senegalia*, formerly classified under the genus *Acacia*, are ecologically and economically valuable legumes widely distributed across African drylands. These species contribute significantly to ecosystem

functioning through nitrogen fixation, soil fertility improvement, provision of fodder and fuelwood, and gum arabic production (Kyalangalilwa *et al.*, 2013; FAO, 2020). Their survival under limited water availability is closely linked to physiological traits such as relative water content, chlorophyll stability, and biomass productivity (Cory *et al.*, 2022; Diatta *et al.*, 2021).

Relative Water Content (RWC) is a widely used indicator of plant water status because it reflects the balance between water uptake and transpiration demand (Mahmood *et al.*, 2019; Raza *et al.*, 2023). Although Plant Water Deficit (PWD) is mathematically related to RWC, it provides a complementary expression of internal water shortage and is sometimes reported together with RWC for comparative interpretation (Fazeli Nasab *et al.*, 2025). Similarly, chlorophyll pigments, particularly chlorophyll *a* and *b*, are essential components of the photosynthetic system but are often degraded under water stress, leading to a decline in photosynthetic efficiency and productivity (Yan *et al.*, 2024; Qiao *et al.*, 2024). Biomass accumulation and Net Primary Productivity (NPP) provide integrative measures of physiological performance, representing how internal physiological adjustments translate into actual growth under varying moisture conditions (Jia *et al.*, 2023; Luo *et al.*, 2024).

Despite the ecological and economic importance of *Vachellia tortilis*, *V. nilotica*, and *Senegalia senegal*, few studies have systematically examined their physiological responses to drought stress under controlled conditions in the semi-arid zone of Nigeria. Earlier field observations indicate substantial variability in water-use efficiency and drought adaptation mechanisms among these species (Cory *et al.*, 2022; Sarr *et al.*, 2024), but controlled experimental validation remains limited. Understanding these responses is essential for selecting species suitable for dryland afforestation and for predicting their resilience under future climatic scenarios.

Therefore, this study aims to evaluate the physiological responses of *Vachellia* and *Senegalia* species under differential watering regimes, focusing on relative water content, plant water deficit, chlorophyll levels, total dry matter accumulation, and net primary productivity. The findings are expected to provide insights into the drought tolerance mechanisms of these species and contribute to the selection of suitable taxa for dryland afforestation and ecological restoration initiatives in West Africa.

## MATERIALS AND METHODS

### Study area

This study was carried out in Borno State, situated in the semi-arid northeastern region of Nigeria. Maiduguri, the state capital, lies between latitudes 11°44'50" and 11°55'25" N and longitudes 13°02'25" and 13°16'00" E. The region is characterised by low and erratic rainfall and high evapotranspiration. Mean annual rainfall ranges

between 450–650 mm, occurring mainly from June to September, while mean daily temperatures range from during the experimental period. Relative humidity fluctuates between 25% and 55% during the dry season. (Adebayo, 1997; Ati *et al.*, 2002; NIMET, 2022).

The area is predominantly agrarian, with an estimated population of about 6.65 million (Kenneth, 2025). Laboratory analyses were conducted at the Department of Biological Sciences, Faculty of Science, University of Maiduguri, while nursery experiments were undertaken between August 2017 and January 2018 at the Imam Malik Botanical Garden, Wulari Ward, Maiduguri.

### Plant material and seed source

Seeds of three drought-tolerant leguminous tree species were used:

1. *Vachellia tortilis* (Forssk.) Galasso & Banfi (Umbrella Thorn Acacia).
2. *Vachellia nilotica* (L.) P.J.H. Hurter & Mabb.
3. *Senegalia senegal* (L.) Willd. (Gum Arabic Tree).

All seeds were procured from the Afforestation Project Office, Ministry of Environment, Borno State, Nigeria. Only viable seeds, confirmed through the floatation test, were selected for sowing.

### Seed pre-treatment

To enhance water uptake and break physical dormancy, seeds were immersed in boiled water and allowed to cool for ten minutes following RMRDC (2004).

### Soil preparation and potting

Plastic pots (32 cm × 40 cm) were filled with a soil mixture consisting of topsoil, cow dung, and river sand in a 3:2:1 ratio (Jackson *et al.*, 1973). Soil used for the experiment was analysed for key physico-chemical properties relevant to water relations:

- Field capacity: 21.3%
- Permanent wilting point: 7.8%
- Soil texture: Sandy-loam
- Organic carbon: 0.82%
- pH: 6.7

A thin layer of dry leaves was placed at the base of each pot to prevent clogging of the drainage holes.

### Determination of seed imbibition rate

Ten seeds of each species were weighed using a precision balance (maximum capacity 160 g). The seeds were

placed in 9 cm Petri dishes lined with Whatman No. 1 filter paper and exposed to steam from a beaker of boiling water enclosed under a bell jar for two hours. The imbibed weight was recorded, and the imbibition rate was determined following the methods of Bouaziz and Bruckler (1989) and Wuest (2007).

### Nursery experiment

Two seeds were sown per pot in mid-August 2017. A total of 144 pots were used (48 pots per replicate: 16 pots per species per replicate and 4 pots per species per treatment). All plants received daily watering during the first 30 days to ensure uniform establishment before treatment application. After germination, seedlings were thinned to one per pot to ensure uniform growth.

### Watering regimes

All pots were watered daily during the first month to ensure uniform establishment. Thereafter, seedlings were exposed to four differential watering regimes:

- **M0**: watered four times per week (control),
- **M1**: watered three times per week (slight moisture stress),
- **M2**: watered twice per week (moderate moisture stress), and
- **M3**: watered once per week (severe moisture stress).

Each irrigation event delivered exactly 1 L of water per pot, resulting in M0 = 4 L/week, M1 = 3 L/week, M2 = 2 L/week, and M3 = 1 L/week.

### Experimental Design

The experiment followed a randomised complete block design (RCBD) with a split-plot arrangement (Gomez and Gomez, 1984). Plot dimensions were as follows:

- Gross plot: 7.3 m × 2.9 m
- Net plot: 0.5 m × 0.5 m
- Inter-plot alley: 0.3 m
- Inter-replicate alley: 0.5 m

Seedlings were harvested destructively at 60, 90, and 120 days after sowing. At each sampling time, 10 seedlings per species per replicate were randomly selected for analysis.

### Physiological measurements

#### **Relative water content (RWC) and plant water deficit (PWD)**

Fresh leaves (third to fifth from the apex) were collected, weighed for fresh weight (FW), rehydrated in distilled water

for three hours to obtain saturation weight (SW), and oven-dried at 80 °C for 48 hours to obtain dry weight (DW). Relative water content (RWC) and plant water deficit (PWD) were measured according to Dhopte and Manuel (2002).

### Chlorophyll content

Chlorophyll *a*, *b*, and total chlorophyll contents were determined according to Lichtenthaler (1987). Approximately 100 mg of fresh leaf tissue was homogenised in 10 ml of 80% acetone, and the extract was filtered through Whatman No. 1 filter paper. The absorbance of the filtrate was measured at 645 and 663 nm using a Shimadzu UV-1700 spectrophotometer. Standard equations were applied for pigment quantification.

### Total Dry Matter (TDM)

Leaves, stems, and roots were oven-dried at 80 °C to constant weight. Total dry matter was computed as the sum of the component dry weights (Poorter *et al.*, 2012).

### Net primary productivity (NPP)

Net primary productivity (NPP, g plant<sup>-1</sup> day<sup>-1</sup>) was estimated as the net increase in total dry biomass per plant over a given time interval, assuming negligible initial biomass at the time of sowing, following the method described by Gubio and Saquib (2025).

### Statistical analysis

Raw data were checked for outliers, missing values, and normality before analysis. The split-plot design model was used, with species as the main-plot factor and watering regime as the subplot factor. Data were analysed using ANOVA in SPSS v23, accounting for separate error terms for main-plot and subplot effects.

Mean separations were performed using the Least Significant Difference (LSD) test at the 5% probability level ( $p < 0.05$ ). Pearson's correlation analysis was used to assess the relationships between net primary productivity (NPP) and watering regimes for each species. All statistical analyses were conducted using standard procedures in SPSS version 23.0 (IBM Corp., Armonk, NY, USA).

## RESULTS

### Relative water content (RWC)

The relative water content (RWC) of *Vachellia tortilis*, *V. nilotica*, and *Senegalia senegal* seedlings responded

**Table 1.** Relative water content (%) of *Vachellia tortilis*, *V. nilotica*, and *Senegalia senegal* at different watering regimes.

Species	Days	M0	M1	M2	M3	LSD (5%)
<i>V. tortilis</i>	60	87.93±4.17d	92.04±0.81b (+5%)	91.68±0.73b (+4%)	89.64±1.35c (+2%)	1.71
	90	91.30±5.12b	95.46±1.34a (+5%)	95.44±0.83a (+5%)	93.57±2.03a (+2%)	2.71
	120	95.15±5.00b	100.09±1.65a (+5%)	99.60±1.17a (+5%)	98.26±2.04a (+3%)	1.87
<i>V. nilotica</i>	60	92.23±0.64a	91.11±0.87a (-1%)	92.65±0.56a (+0.5%)	91.88±1.73a (-0.4%)	1.89
	90	95.99±0.12a	95.33±0.71a (-1%)	96.2 ± 0.14a (+0.3%)	95.51±2.17a (-0.5%)	1.01
	120	99.77±0.45a	99.50±0.47a (-0.3%)	100.85±0.64a (+1%)	99.80±1.49a (-0.8%)	2.10
<i>S. senegal</i>	60	90.71±2.43ab	93.26±1.52b (+3%)	91.15±0.90ab (-0.5%)	89.41±1.53a (-1%)	2.80
	90	94.13±2.30a	96.38±1.17a (+2%)	94.82±1.45a (+1%)	94.0 ± 1.03a (-0.1%)	2.39
	120	98.12±2.49ac	101.08±1.38b (+3%)	98.66±1.47c (+1%)	97.95±1.89a (-0.2%)	2.31

Figures in parentheses indicate percentage increase (+) or decrease (-) with respect to control. Keys: M0 = watered four times a week (control), M1 = watered three times a week (slight moisture stress), M2 = watered two times a week (moderate moisture stress), M3 = watered once a week (severe moisture stress). Means ± SD with different superscript letters within the same row are significantly different at  $p < 0.05$  (LSD test).

distinctly to differential watering regimes across all sampling periods (Table 1). A consistent increase in RWC was observed under slight (M1) and moderate (M2) moisture stress compared with the control (M0), though the magnitude of response varied significantly among species and sampling times.

In *V. tortilis*, RWC at 60, 90, and 120 days increased by approximately 5% under M1 and M2 treatments compared with the control ( $p \leq 0.05$ ). Under severe stress (M3), differences were not statistically significant ( $p > 0.05$ ), with only small increases of 2–3%. Seedlings under M1 and M2 maintained consistently higher RWC than the control, as confirmed by LSD groupings ( $p < 0.05$ ).

*V. nilotica* exhibited remarkable stability in RWC across all treatments, maintaining values above 91% at all sampling times. No significant differences were detected among watering regimes, and variation relative to control was minimal (-1% to +1%), indicating strong inherent drought tolerance.

In *S. senegal*, RWC increased slightly under M1 (+2–3%) and remained comparable to the control under M2 and M3 treatments across all growth stages. At 120 days, a significant difference between M1 and M2 was observed (LSD test,  $p < 0.05$ ), suggesting a threshold of stress sensitivity at this later stage.

Overall, all three species maintained relatively high RWC values under water-limited conditions, demonstrating effective physiological adjustment to moisture stress. Among them, *V. nilotica* displayed the highest stability, while *V. tortilis* and *S. senegal* showed more flexible responses depending on stress intensity and developmental stage.

### Plant water deficit (PWD %)

Plant water deficit (PWD), a complementary expression of RWC, followed patterns consistent with leaf water status

(Table 2). In *Vachellia tortilis*, *V. nilotica*, and *Senegalia senegal* seedlings was significantly affected by watering regimes (Table 2). Overall, increasing water stress (M1–M3) led to a marked decrease in PWD in *V. tortilis* and *S. senegal*, whereas *V. nilotica* exhibited more variable responses across growth stages.

In *V. tortilis*, PWD values were highest in the control (M0:  $7.52 \pm 4.55\%$ ) and declined by approximately 50–54% under M1 and M2 treatments at all sampling times ( $p < 0.05$ ). Even under severe stress (M3), reductions of about 25–30% were recorded compared with the control, indicating effective water retention and reduced transpirational loss.

In *V. nilotica*, PWD responses were inconsistent across treatments. Slight increases were observed under mild (M1) and severe (M3) stress at 60 days (+20–40%), while M2 caused a marginal reduction (-4%). Differences among treatments were not statistically significant ( $p > 0.05$ ) at later stages, suggesting this species maintains a stable water status under varying soil moisture conditions.

In *S. senegal*, PWD decreased significantly under slight and moderate stress (-52% and -30% at 60 days), reflecting effective water conservation. However, at 120 days, PWD increased slightly under M3 (+6%), indicating that prolonged stress eventually compromised water balance.

Collectively, *V. tortilis* displayed the most pronounced reduction in PWD and thus the highest drought tolerance, while *V. nilotica* maintained steady values, reflecting conservative water use. *S. senegal* exhibited intermediate behaviour, maintaining low PWD under mild stress but showing sensitivity under prolonged severe drought.

### Chlorophyll 'a'

Chlorophyll *a* (*Chl a*) varied significantly with watering regime and sampling time in all three species (Table 3). In

**Table 2.** Plant water deficit (%) of *Vachellia tortilis*, *V. nilotica* and *Senegalia senegal* under different watering regimes.

Species	Days	M0	M1	M2	M3	LSD
<i>V. tortilis</i>	60	7.52±4.55c	3.43±1.16b (-54%)	3.34±0.61b (-54%)	5.27±1.86a (-29%)	1.09
	90	8.70±5.12c	4.54±1.35b (-48%)	4.56±0.82b (-48%)	6.43±2.05a (-26%)	0.19
	120	10.63±5.28c	5.16±1.05b (-51%)	5.39±0.48b (-49%)	7.54±2.61a (-29%)	0.87
<i>V. nilotica</i>	60	2.97±0.70b	3.56±0.54b (+20%)	2.84±0.18b (-4%)	4.17±2.64a (+40%)	0.75
	90	4.01±0.12a	4.67±0.71a (+16%)	3.72±0.14a (-7%)	4.82±2.75a (+20%)	1.45
	120	5.00±0.23b	5.62±0.55b (+12%)	4.53±0.50a (-9%)	4.58±0.43a (-8%)	0.98
<i>S. senegal</i>	60	6.28±1.46a	3.03±0.27c (-52%)	4.37±1.55b (-30%)	5.22±1.32a (-17%)	0.43
	90	5.87±2.30b	3.62±1.17b (-38%)	5.18±1.45a (-12%)	5.95±1.03a (+2%)	1.23
	120	6.98±2.94ac	4.60±1.09b (-34%)	6.16±1.69a (-12%)	7.42±1.53a (+6%)	1.37

Figures in parentheses indicate percentage reduction (-) or increase (+) in PWD with respect to control. **Keys:** M0 = watered four times a week (control), M1 = watered three times a week (slight moisture stress), M2 = watered two times a week (moderate moisture stress), M3 = watered once a week (severe moisture stress). Means ± SD with different superscript letters within the same row are significantly different at  $p < 0.05$  (LSD test).

**Table 3.** Chlorophyll 'a' (mg/gram fresh leaves) of *Vachellia tortilis*, *V. nilotica*, and *Senegalia senegal* at different watering regimes over days.

Species	Days	M0	M1	M2	M3	LSD (5%)
<i>V. tortilis</i>	60	27.52±4.54c	23.43±1.16b (-15%)	23.43±0.61b (-15%)	25.27±1.86a (-8%)	1.04
	90	25.07±3.93c	22.79±2.60b (-9%)	26.17±6.53a (+4%)	26.17±6.93c (+4%)	0.15
	120	27.90±3.40a	24.72±3.96b (-11%)	29.54±6.81b (+6%)	31.14±7.51a (+12%)	0.03
<i>V. nilotica</i>	60	30.67±1.06d	34.66±4.58c (+13%)	27.97±0.80b (-9%)	23.44±1.68a (-24%)	0.72
	90	33.55±0.57d	39.69±2.18c (+18%)	31.52±0.80b (-6%)	28.84±3.79a (-14%)	0.87
	120	35.96±0.64c	30.06±8.61b (-16%)	30.87±3.72b (-14%)	29.30±6.44a (-19%)	1.03
<i>S. senegal</i>	60	26.70±4.84ab	26.70±1.91a (0%)	28.26±0.78b (+6%)	23.24±2.77a (-13%)	5.05
	90	28.70±4.16c	28.33±2.49b (-1%)	30.96±1.71b (+8%)	26.0 ± 2.47a (-9%)	0.78
	120	31.9±4.14c	31.37±3.53c (-2%)	34.17±1.75b (+7%)	29.53±3.62a (-7%)	1.11

Figures in parentheses indicate percentage increase (+) or decrease (-) with respect to control. **Keys:** M0 = watered four times a week (control), M1 = watered three times a week (slight moisture stress), M2 = watered two times a week (moderate moisture stress), M3 = watered once a week (severe moisture stress). Means ± SD with different superscript letters within the same row are significantly different at  $p < 0.05$  (LSD test).

*V. tortilis*, *Chl a* at 60 days (M0 = 27.52 ± 4.54 mg g<sup>-1</sup> FW) declined under M1 and M2 (≈ -15%) and slightly under M3 (-8%). At 90 days, *Chl a* was modestly higher under M2 and M3 (≈ +4% vs. M0), and by 120 days it increased further under M3 (31.14 ± 7.51 mg g<sup>-1</sup>; +12% vs. M0), indicating late-stage adjustment under stress.

In *V. nilotica*, the control maintained the highest *Chl a* at each time, but M1 produced short-term stimulation (+13% at 60 d; +18% at 90 d), whereas M3 consistently reduced *Chl a* (to -24% at 60 d and up to -19% at 120 d), reflecting sensitivity to sustained drought.

In *S. senegal*, *Chl a* remained comparatively stable: ~0% change under M1 at 60 d, small increases under M2 (+6%), and modest decreases under M3 (-13%). Similar small shifts occurred at 90 and 120 d (slight increases in M2; slight reductions in M3).

Overall, *S. senegal* showed the least variability, *V. tortilis* exhibited late-stage increases under stress, and *V. nilotica* showed the greatest declines under severe drought. Differences among treatments within species were significant (LSD,  $p < 0.05$ ).

### Chlorophyll b

Chlorophyll *b* (*Chl b*) varied significantly among watering regimes and sampling times in all species (Table 4;  $p < 0.05$ ). In *V. tortilis*, *Chl b* was 20.43 ± 2.07 mg g<sup>-1</sup> FW at 60 d (M0) and increased under stress: M1 (+11%), M2 (+15%), M3 (+12%). At 90 d, values were slightly lower under M1 (-3%) but higher under M2 (+16%) and M3 (+7%). At 120 d, *Chl b* remained elevated across treatments,

**Table 4.** Chlorophyll b (mg/gram fresh leaves) of *Vachellia tortilis*, *V. nilotica*, and *Senegalia senegal* at different watering regimes over days.

Species	Days	M0	M1	M2	M3	LSD (5%)
<i>V. tortilis</i>	60	20.43±2.07b (+0%)	22.62±0.47ab (+11%)	23.57±1.51b (+15%)	22.79±3.16b (+12%)	1.34
	90	22.34±2.04c (+0%)	21.60± 2.20b (-3%)	25.90±1.36a (+16%)	23.82±3.37a (+7%)	0.67
	120	25.80±1.73b (+0%)	25.77±1.96bc (-0.1%)	28.20±1.54a (+9%)	26.32±3.69ac (+2%)	2.16
<i>V. nilotica</i>	60	23.70±1.32a (+0%)	34.27±2.90d (+45%)	32.20±1.45c (+36%)	27.53± 1.93b (+16%)	2.11
	90	26.76±0.74d (+0%)	36.54±2.35c (+37%)	35.97±0.46b (+34%)	29.81± 1.90a (+11%)	0.56
	120	25.70±3.27d (+0%)	34.69±7.72c (+35%)	38.57±0.82b (+50%)	25.83± 7.72a (+1%)	1.00
<i>S. senegal</i>	60	23.60±1.41d (+0%)	23.54±1.33c (-0.3%)	22.57±0.76b (-4%)	15.40± 2.45a (-34%)	0.25
	90	25.62±0.76b (+0%)	25.68± 2.73b (+0.2%)	26.15±1.88c (+2%)	17.31±2.45a (-32%)	0.32
	120	28.34±1.21c (+0%)	27.65±1.22b (-2%)	29.60±1.28d (+4%)	21.62± 0.79a (-24%)	0.73

Figures in parentheses indicate percentage increase (+) or decrease (-) with respect to control. Keys: M0 = watered four times a week (control), M1 = watered three times a week (slight moisture stress), M2 = watered two times a week (moderate moisture stress), M3 = watered once a week (severe moisture stress). Means ± SD with different superscript letters within the same row are significantly different at  $p < 0.05$  (LSD test).

**Table 5.** Total chlorophyll (mg /gram fresh leaves) of *Vachellia tortilis*, *V. nilotica*, and *S. senegal* at different watering regimes over days.

Species	Days	M0	M1	M2	M3	LSD (5%)
<i>V. tortilis</i>	60	47.33±5.79cd	45.40±0.87b (-4%)	47.00±6.76c (-1%)	48.06±9.52d (+2%)	1.02
	90	47.34 ±5.79a	44.40±0.87b (-6%)	52.07± .76c (+10%)	50.00±9.52d (+6%)	1.02
	120	53.70 ±4.57a	50.50±2.28b (-6%)	57.75±7.37c (+8%)	57.47±10.43c (+7%)	0.98
<i>V. nilotica</i>	60	54.37±0.60b	68.94±7.41d (+27%)	60.17±2.19c (+11%)	50.97±3.53a (-6%)	1.33
	90	59.31±1.10b	76.23±3.54d (+29%)	67.54±2.32 (+14%)	58.65±5.10a (-1%)	2.33
	120	61.66±3.44b	66.75±12.60c (+8%)	69.45± .50d (+12%)	55.13±13.98a (-10%)	0.78
<i>S. senegal</i>	60	50.30±5.50b	50.28±1.27c (-0.4%)	50.8±1.27d (+1%)	38.65±4.04a (-23%)	1.16
	90	54.32±4.52b	54.02±0.83d (-0.6%)	57.11±3.59c (+14%)	43.34±3.08a (-20%)	0.41
	120	60.25±4.87c	58.35±4.79b (-3%)	63.78±2.83d (+6%)	51.15±3.62a (-15%)	1.21

Figures in parentheses indicate percentage increase (+) or decrease (-) with respect to control. M0 = watered four times a week (control), M1 = watered three times a week (slight moisture stress), M2 = watered two times a week (moderate moisture stress), M3 = watered once a week (severe moisture stress). Means ± SD with different superscript letters within the same row are significantly different at  $p < 0.05$  (LSD test).

peaking under M2 (~+9%).

In *V. nilotica*, responses were stronger. At 60 d, *Chl b* rose markedly (M1 +45%, M2 +36%, M3 +16% vs. M0 =  $23.70 \pm 1.32 \text{ mg g}^{-1}$ ). This stimulation persisted at 90 d (M1 +37%, M2 +34%, M3 +11%) and was greatest at 120 d under M2 (+50%), followed by M1 (+35%); M3 showed ~+1%.

In *S. senegal*, *Chl b* declined with increasing stress. At 60 d, small decreases occurred in M1 (-0.3%) and M2 (-4%), while M3 dropped sharply (-34% vs. M0 =  $23.60 \pm 1.41 \text{ mg g}^{-1}$ ). The pattern held at 90 d (M3 ≈ -32%); by 120 d, M2 produced a slight increase (+4%) but M3 remained substantially lower (-24%).

Collectively, *V. nilotica* exhibited the strongest up-regulation of *Chl b* under mild-moderate stress, *V. tortilis* showed moderate increases across stress levels, and *S.*

*senegal* displayed consistent declines under severe drought—supporting species-specific differences in pigment stability under moisture limitation.

### Total Chlorophyll (mg g<sup>-1</sup>)

Total chlorophyll concentration in *Vachellia tortilis*, *V. nilotica*, and *Senegalia senegal* was significantly affected by watering regime and growth stage (Table 5;  $p < 0.05$ ). Moderate moisture stress (M2) generally enhanced pigment concentration, whereas severe stress (M3) tended to reduce or stabilise values depending on species.

In *V. tortilis*, total chlorophyll increased consistently under M2 across sampling dates— $47.00 \pm 6.76 \text{ mg g}^{-1}$  (-1%) at 60 d and  $57.75 \pm 7.37 \text{ mg g}^{-1}$  (+8%) at 120 d. M3

**Table 6.** Total dry matter accumulation (g) of *Vachellia tortilis*, *V. nilotica*, and *Senegalia senegal* at different watering regimes over days.

Species	Days	M0	M1	M2	M3	LSD (5%)
<i>V. tortilis</i>	60	2.63±0.49	1.33±0.06 (-49%)	1.05±0.05 (-60%)	0.71±0.06 (-73%)	0.02
	90	3.47±0.15	2.47±0.06 (-29%)	1.53±0.06 (-56%)	0.89±0.10 (-74%)	0.11
	120	4.27±0.31	3.13±0.15 (-27%)	2.47±0.06 (-42%)	1.73±0.15 (-59%)	0.44
<i>V. nilotica</i>	60	11.07±1.33	12.23±1.29 (+11%)	7.29±0.70 (-30%)	2.87±0.21 (-74%)	1.37
	90	15.60±1.13	14.93 ±0.86 (-4%)	10.97±1.26 (-30%)	4.03±0.76 (-74%)	1.67
	120	29.27±1.26	21.33 ± 1.89 (-27%)	15.03±1.00 (-49%)	5.57±0.47 (-81%)	0.92
<i>S. senegal</i>	60	4.33 ±0.41	4.63 ± 0.21 (+7%)	2.80±0.17 (-38%)	1.43±0.15 (-59%)	1.09
	90	5.13 ±0.25	3.60 ± 0.35 (-30%)	5.70±0.10 (+11%)	2.83±0.32 (-45%)	0.03
	120	8.07 ±0.14	3.86 ± 0.06 (-52%)	7.87±0.51 (-2%)	3.60±0.20 (-55%)	0.34

Figures in parentheses indicate percentage increase (+) or decrease (-) with respect to control. **Keys:** M0 = watered four times a week (control), M1 = watered three times a week (slight moisture stress), M2 = watered two times a week (moderate moisture stress), M3 = watered once a week (severe moisture stress). Means ± SD with different superscript letters within the same row are significantly different at  $p < 0.05$  (LSD test).

produced a slight increase at 60 d (+2%) but little improvement thereafter.

In *V. nilotica*, M1 and M2 markedly stimulated chlorophyll synthesis: at 60 d, M1 ( $68.94 \pm 7.41 \text{ mg g}^{-1}$ ) exceeded the control by 27%, M2 by 11%, while M3 decreased (-6%). The same ranking (M1 > M2 > M3) persisted through 90 and 120 d, confirming significant treatment effects.

In *S. senegal*, chlorophyll content declined strongly under M3. At 60 d, M3 was -23% below the control, whereas M2 enhanced content slightly (+1%). At 120 d, M2 again increased total chlorophyll (+6%), but M3 reduced it (-15%).

Overall, moderate stress (M2) enhanced chlorophyll formation in *V. tortilis* and *V. nilotica*, while *S. senegal* was more sensitive to severe drought. These findings highlight distinct species-level adaptations of chlorophyll metabolism to water limitation.

### Total dry matter accumulation

Total dry-matter accumulation (TDM) differed significantly among watering regimes and species (Table 6;  $p < 0.05$ ). All species showed declines in biomass with increasing drought severity, but their sensitivities varied.

In *V. tortilis*, TDM decreased progressively from control ( $2.63 \pm 0.49 \text{ g}$ ) to M3 ( $0.71 \pm 0.06 \text{ g}$ ; -73%) at 60 d, and reductions of similar magnitude occurred at 90 d (-74%) and 120 d (-59%).

In *V. nilotica*, biomass production was greatest in the control, peaking at  $29.27 \pm 1.26 \text{ g}$  (120 d). Moderate stress (M2) reduced TDM by  $\approx 30\%$  at 60 d and  $\approx 49\%$  at 120 d, whereas severe stress (M3) caused large declines (-74 to -81%). Mild stress (M1) slightly stimulated growth (+11% at 60 d).

*S. senegal* maintained relatively stable biomass under

moderate stress: at 90 d, M2 produced  $5.70 \pm 0.10 \text{ g}$  (+11%), but severe stress (M3) sharply reduced TDM across stages, culminating in  $3.60 \pm 0.20 \text{ g}$  (-55%) at 120 d.

Thus, *V. nilotica* attained the greatest biomass under ample water, *S. senegal* sustained moderate-stress tolerance, and *V. tortilis* was most sensitive to water limitation.

### Net primary productivity (NPP)

Net primary productivity (NPP) declined progressively with increasing water stress in all species, though patterns differed by species and growth stage (Table 7).

In *V. tortilis*, NPP was highest under control conditions ( $0.0438 \text{ g plant}^{-1} \text{ day}^{-1}$ ) during 0–60 d and dropped sharply under severe stress (M3; -73%). A short-term rise under M1 (+36% at 60–90 d) suggested partial compensatory growth, but reductions persisted under M2–M3 thereafter.

In *V. nilotica*, maximum productivity occurred at 90–120 d under M0 ( $0.4543 \text{ g plant}^{-1} \text{ day}^{-1}$ ). Water limitation reduced NPP strongly under M2–M3 (-70 to -88%), demonstrating high sensitivity to reduced soil moisture.

In *S. senegal*, NPP generally fell under stress, yet an exceptional increase (+262% under M2 at 60–90 d) indicated transient recovery capability. Nevertheless, severe stress (M3) consistently lowered productivity at all stages.

### Correlation and regression

Correlations between NPP and watering frequency were negative and highly significant during early growth (Table 8). In *V. tortilis*,  $r = -0.93$  (60 d) and  $r = -0.81$  (90 d) confirmed strong water-dependence, whereas at 120 d,  $r$

**Table 7.** NPP/day/plant (g/day) of *Vachellia tortilis*, *V. nilotica*, and *Senegalia senegal* under different watering regimes over days.

Species	Days	M0	M1	M2	M3
<i>V. tortilis</i>	0–60 d	0.0438	0.0222 (–49.3%)	0.0175 (–60.0%)	0.0118 (–73.1%)
	60–90 d	0.0280	0.0380 (+35.7%)	0.0160 (–42.9%)	0.0060 (–78.6%)
	90–120 d	0.0267	0.0220 (–17.6%)	0.0313 (+17.2%)	0.0280 (+4.9%)
<i>V. nilotica</i>	0–60 d	0.1845	0.2038 (+10.5%)	0.1300 (–29.5%)	0.0478 (–74.1%)
	60–90 d	0.1510	0.0900 (–40.4%)	0.1060 (–30%)	0.0387 (–74.4%)
	90–120 d	0.4543	0.2313 (–49.1%)	0.1353 (–70.2%)	0.0513 (–88.7%)
<i>S. senegal</i>	0–60 d	0.0722	0.0772 (+6.9%)	0.0467 (–35.3%)	0.0238 (–67.0%)
	60–90 d	0.0267	0.0343 (–228.5%)	0.0967 (+262.3%)	0.0467 (+75.0%)
	90–120 d	0.0980	0.0087 (–91.1%)	0.0723 (–26.3%)	0.0257 (–73.8%)

Figures in parentheses indicate percentage increase (+) or decrease (–) with respect to control. **Keys:** M0 = watered four times a week (control), M1 = watered three times a week (slight moisture stress), M2 = watered two times a week (moderate moisture stress), M3 = watered once a week (severe moisture stress), d = days.

**Table 8.** Correlation Coefficient (r), Percent Dependence (d), and Linear Regression Equation ( $\hat{Y}$ ) between net primary productivity (NPP/day/plant) and watering regime of three plant species (*Vachellia tortilis*, *Vachellia nilotica*, and *Senegalia senegal*) at different seedling ages.

Species	Days	Correlation Coefficient (r ± SE of r)	Percent Dependence (d %)	Linear Regression Equation ( $\hat{Y} = a+bx$ )
<i>V. tortilis</i>	60	–0.93 ± 0.260	86*	$\hat{Y} = 0.039 - 0.010X$
	90	–0.81 ± 0.303	66*	$\hat{Y} = 0.035 - 0.009X$
	120	+0.44 ± 0.462	20*	$\hat{Y} = 0.025 + 0.001X$
<i>V. nilotica</i>	60	–0.89 ± 0.242	80*	$\hat{Y} = 0.214 - 0.048X$
	90	–0.81 ± 0.222	66*	$\hat{Y} = 0.035 - 0.009X$
	120	–0.96 ± 0.153	92*	$\hat{Y} = 0.408 - 0.129X$
<i>S. senegal</i>	60	–0.92 ± 0.270	84*	$\hat{Y} = 0.080 - 0.016X$
	90	+0.46 ± 0.461	21*	$\hat{Y} = 0.005 + 0.019X$
	120	–0.48 ± 0.453	23*	$\hat{Y} = 0.074 - 0.015X$

SE = Standard Error of r; \* = significant at 5% level ( $p < 0.05$ ).

= +0.44 suggested a shift toward internal physiological control.

In *V. nilotica*, correlations remained strongly negative ( $r = -0.87$  to  $-0.96$ ) throughout, explaining up to 92% of variance in NPP—evidence of high water-sensitivity. *S. senegal* showed  $r = -0.92$  (60 d) but a near-neutral to positive correlation by 90 d ( $r = +0.46$ ), reflecting adaptive adjustment under sustained drought. Linear regressions confirmed that reduced watering frequency consistently lowered NPP, most notably in *V. nilotica*, underscoring species-specific drought-response patterns.

## DISCUSSION

The present study demonstrates that *Vachellia tortilis*, *V. nilotica*, and *Senegalia senegal* respond in distinct,

species-specific ways to differential water availability. The results highlight each species' adaptive capacity to moisture stress—an essential trait for successful dry-land afforestation and ecological restoration under increasing climate variability in semi-arid Nigeria. This discussion focuses on species-specific strategies related to water relations, pigment dynamics, biomass allocation, and overall productivity.

Consistently high relative-water content (RWC), particularly in *V. nilotica* and *S. senegal*, indicates efficient internal water regulation and osmotic adjustment—mechanisms typical of drought-tolerant legumes (Mahmood *et al.*, 2019). These findings agree with reports that high RWC under stress supports improved growth and survival in arid-zone species (Fazeli-Nasab *et al.*, 2025; Shah *et al.*, 2020). The slight RWC increase under moderate stress (M2) in *V. tortilis* suggests acclimation through osmotic

adjustment, consistent with responses observed in African acacias (Uni *et al.*, 2023; Zeleke *et al.*, 2021).

The decline in plant-water deficit (PWD) with increasing moisture stress, especially in *V. tortilis* and *S. senegal*, suggests regulation of transpirational water loss and maintenance of leaf turgor (Kramer and Boyer, 1995). Comparable decreases in PWD have been reported in dry-land *Vachellia* species grown under controlled and field conditions (Diatta *et al.*, 2021; Sarr *et al.*, 2024). The stability of PWD in *V. nilotica* implies a conservative water-use strategy, also noted for other drought-hardy legumes (Zeleke *et al.*, 2021).

Variations in chlorophyll pigments mirrored species-level drought resilience. In *V. tortilis* and *V. nilotica*, chlorophyll a and b were maintained or increased under moderate stress, supporting reports that moderate dehydration can enhance pigment concentration via osmoprotectant buildup and antioxidant activation (Qiao *et al.*, 2024). The pigment decline under severe stress (M3) in *S. senegal* indicates photoinhibition and chlorophyll degradation typical of sensitive taxa. These outcomes reinforce the reliability of chlorophyll retention as a non-destructive marker of drought tolerance (Jia *et al.*, 2023).

Total dry matter accumulation (TDM) decreased with increasing drought intensity in all species, consistent with the general understanding that reduced soil moisture limits carbon assimilation, nutrient uptake, and cell expansion (Seleiman *et al.*, 2021, Wahab *et al.*, 2022). *V. nilotica* accumulated the greatest biomass under optimal watering, underscoring its value as a fast-growing reforestation species for moister semi-arid zones (Mitiku *et al.*, 2021). Conversely, the relative stability of TDM under moderate stress in *S. senegal* supports its suitability for harsher, drier sites where survival and conservative growth confer ecological advantage (Diatta *et al.*, 2021; Cory *et al.*, 2022).

Net-primary-productivity (NPP) responses provide an integrative view of adaptive performance. The observed NPP increase under moderate stress (M2) in *V. tortilis* and *S. senegal* during later growth stages points to compensatory mechanisms—likely enhanced root expansion or osmotic regulation—also documented in desert legumes (Sarr *et al.*, 2024; Uni *et al.*, 2023). The sharp NPP decline in *V. nilotica* under severe drought (M3) reveals sensitivity to prolonged stress. These findings support recent syntheses identifying NPP as a robust cross-species indicator of drought resilience (Mahmood *et al.*, 2019; Jia *et al.*, 2023).

### Implications for dryland forestry and species selection

The combined physiological and productivity responses indicate clear interspecific differences in drought adaptation strategies. *V. tortilis* and *S. senegal* demonstrated strong physiological plasticity under moderate water stress, maintaining water status, chlorophyll content, and reasonable biomass production. This resilience makes both species attractive candidates for dryland restoration

initiatives where water availability is inconsistent.

*V. nilotica*, although highly productive under optimal watering, was more sensitive to water limitation. This suggests that *V. nilotica* may perform best in restoration or plantation systems where supplemental watering is feasible, rather than in strictly rainfed or severely drought-prone landscapes.

Overall, the results highlight that species selection for dryland afforestation should consider not only productivity but also the capacity to maintain physiological functioning under moisture-limited conditions. The restoration potential of *V. tortilis* and *S. senegal* aligns with their ecological distribution across arid zones of Africa and supports their use in climate-resilient landscape management.

### Conclusion and Recommendation

Collectively, *V. tortilis* and *S. senegal* exhibit high physiological plasticity, maintaining essential functional traits under moderate stress, whereas *V. nilotica* performs best in well-watered conditions. These trends align with established models of drought adaptation in dry-land legumes. The results provide a practical framework for selecting species in semi-arid reforestation and restoration programs. Incorporating NPP into evaluation protocols strengthens its application as a quantitative criterion for drought-tolerant species selection under changing climatic regimes.

This study provides experimental evidence of species-specific physiological and productivity responses to differential water availability in three key dry-land legumes—*Vachellia tortilis*, *V. nilotica*, and *Senegalia senegal*—under semi-arid conditions in northeastern Nigeria. *V. tortilis* and *S. senegal* exhibited high physiological plasticity, maintaining or enhancing RWC, chlorophyll content, and NPP under moderate stress. *V. nilotica* performed best under ample water but was more vulnerable to prolonged drought, especially regarding pigment stability and productivity.

The ability of *V. tortilis* and *S. senegal* to sustain water balance and growth under sub-optimal moisture underscores their suitability for dry-land afforestation, land rehabilitation, and climate-resilient ecosystem restoration. Net primary productivity proved to be an effective integrative index for evaluating drought tolerance and should be adopted in species-selection frameworks for climate-sensitive regions.

These insights advance understanding of functional drought responses in leguminous trees and provide practical guidance for designing reforestation and agro-forestry strategies across West African drylands facing intensified climate variability.

### CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

## ACKNOWLEDGEMENT

The author sincerely acknowledges the invaluable cooperation, guidance, and academic support of his former Head of the Department of Biological Sciences and Dean, Faculty of Science, Late Professor M. A. Kokori. His dedication to academic excellence, mentorship, and encouragement contributed significantly to the successful compilation of this research.

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