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Statistical modeling confirms the synergy of paired row planting and varieties in boosting groundnut yield, water productivity and economic returns

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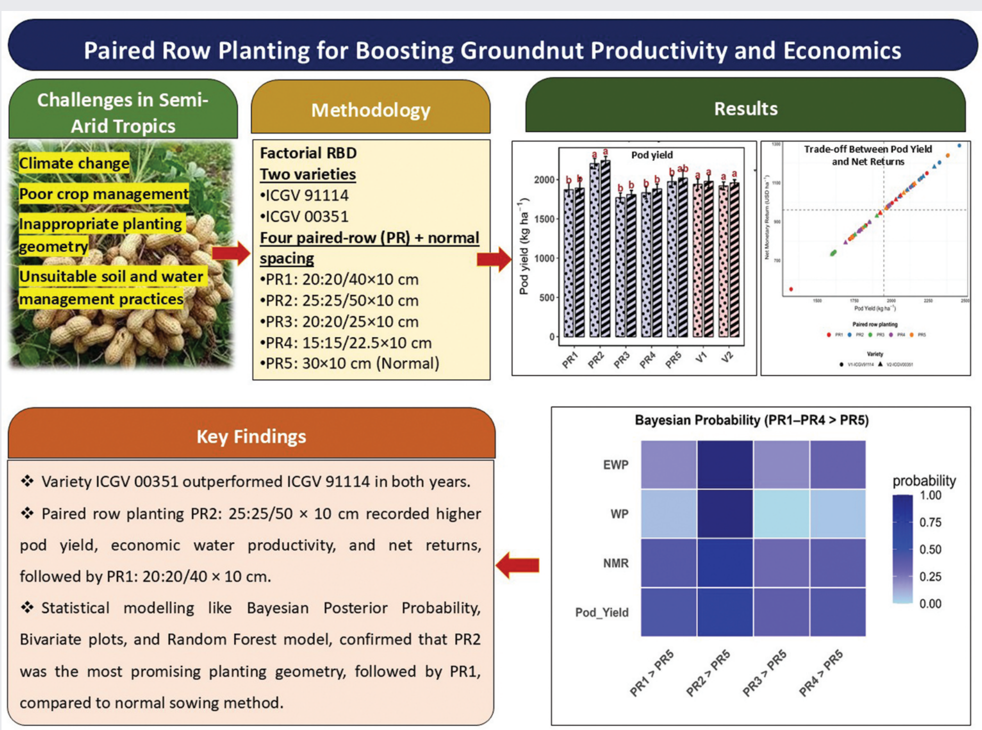
ABSTRACT

Climate change and poor crop management threaten groundnut productivity in the semi-arid tropics (SATs). To address this, a field experiment was conducted at ICRISAT in Hyderabad, India, during 2016–17 and 2017–18. The study used two prevalent groundnut varieties, ICGV91114 and ICGV00351. It evaluated four paired-row (PR) systems with different planting geometries: PR1-20:20 cm/40 cm × 10 cm; PR2-25:25 cm/50 cm × 10 cm; PR3-20:20 cm/25 cm × 10 cm; PR4-15:15 cm/22.5 cm × 10 cm, along with the standard spacing PR5-30 cm × 10 cm. Results showed that ICGV00351 outperformed ICGV91114 in both years. Among planting geometry, pod yield, economic water productivity, and profitability were higher in PR2 than PR1. Similarly, the highest average soil moisture was recorded in PR2 i.e. 1.87–2.01 cm in the 0–30 cm soil depth in both years. This enhanced soil moisture in PR2 improved nutrient availability and uptake, resulting in higher leaf area index, biomass yield, water productivity, and net returns. Bayesian probability and bivariate plots further confirmed that PR2 was the most promising planting geometry, followed by PR1, compared to the normal sowing method. A random forest model trained on above-ground available data can predict pod yield with greater accuracy at the 75th day after sowing in PR2. The findings highlight the potential of paired-row planting to improve groundnut productivity and resilience in SAT landscapes. However, collaborative efforts among governments, research institutions, community organisations, and farmers are essential to scale up paired-row planting for groundnuts, to increase productivity at the landscape level and thereby support the livelihoods of smallholder farmers.



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1. Introduction

Groundnut (*Arachis hypogaea* L.) is one of the most important oilseed crops, and the kernels of groundnut are nutritionally rich in protein (~25%), oil (~50%), antioxidants, essential minerals, and vitamins. Groundnut is cultivated extensively in semi-arid tropics (SATs), covering approximately 32.7 million hectares with an annual yield of 53.9 million tons and an average productivity of 1.6 metric t ha^{-1} in 2021 (ICRISAT Groundnut Overview [ICRISAT], 2021). With its versatility and wide adaptability across diverse agro-climatic zones, groundnut is a reliable crop for farmers in drylands.

In India, groundnut is grown during the rainy season as a rainfed crop and in the post-rainy season with supplemental irrigation at critical stages. Several researchers reported that crop failure in SATs is due to soil water-related issues like water scarcity and change in rainfall pattern (Kale et al., 2026; Kamdi et al., 2023; Kumar et al., 2024; Pasumarthi et al., 2024; Ringler et al., 2010; Sawargaonkar et al., 2025) and uncertainty in rainfall (Parry et al., 2007). The productivity of groundnut is hampered mainly due to aberrant weather conditions, climate change, inappropriate crop and water management practices (Ramesh & Devasenapathy, 2007; Thakur et al., 2011), lack of soil water conservation measures to use the conserved water during the moisture deficit period (Kanwar, 1999), and the non-availability of climate-smart varieties. Water is an important natural resource and a primary limiting factor for crop production in dryland agriculture (Falkenmark & Rockström, 2008; G. Sawargaonkar et al., 2024). Therefore, SATs need an integrated approach to soil and soil moisture management practices, which efficiently conserves water in crop growing periods and increases crop productivity (Gokhale et al., 2013; Khopade et al., 2025; Manasa et al., 2024). Groundnut productivity in the semi-arid tropics is highly sensitive to climate variability, particularly drought, erratic rainfall, and excess rainfall. Moisture stress during critical growth stages can reduce peg formation, pod filling, and final pod yield, while excess rainfall may adversely affect root activity, nutrient uptake, and crop performance (Obedgiu et al., 2023). Under smallholder production systems, these weather-related stresses, together with suboptimal crop and water management, often widen the gap between potential yield and realized farm yield. Therefore, agronomic interventions that improve soil moisture conservation and water-use efficiency are important for stabilizing groundnut productivity and enhancing resilience under changing climatic conditions (Gelaye & Luo, 2024).

Broad bed furrows, flatbeds, ridges and furrows, and conservation furrows are in-situ soil moisture conservation practices that enhance soil moisture content and crop and water productivity (Pathak et al., 2013; G. L. Sawargaonkar et al., 2024). Broad bed furrows increased water productivity in different cropping systems and conserved higher soil moisture at the lowest and highest SWC points (Kamdi et al., 2020).

In SATs, field studies on paired-row planting have shown that it increases groundnut pod yield. Paired row planting is a modification in planting geometry, where crop rows are arranged on a wide bed by adjusting the inter-row spacing. Plant spacing in the field is a crucial factor in enhancing aeration and light penetration into the plant canopy to optimize photosynthesis. Groundnut research in India indicates that paired-row planting improves pod yield under rainfed conditions, and criss-cross planting can produce about 14% higher yield compared with the traditional parallel-row planting method (Indian Institute of Groundnut Research [ICAR-IIGR], n.d.)

Mandal, et al. (2019) conducted a field experiment during the *summer* season in Odisha state of India and reported the highest groundnut pod yield (2109 kg ha^{-1}) in paired-row planting at 45 cm × 15 cm spacing, which was higher than ridge and furrow planting at 30 cm × 10 cm spacing and flat-bed method at 30 cm × 10 cm spacing. A field experiment conducted by Hamakareem et al. (2016) at the University of Sulaimani in Iraq found that there was a significant difference between two planting geometries (60 cm × 30 cm and 50 cm × 30 cm) and a maximum number of pods plant−1 was observed in 60 cm × 30 cm, while the minimum was recorded by 50 cm × 30 cm. In a field study (Jaiswal et al., 2018) on different planting geometries, maximum pod yield (2.12 t ha^{-1}) was recorded in the spacing of 30 cm × 10 cm compared to wider spacing 30 cm × 15 cm (1.61 t ha^{-1}) as well as closer spacing 22.5 cm × 10 cm (2.08 t ha^{-1}) in the tropical region of Maharashtra in India.

These studies showed that appropriate planting geometry plays a key role in enhancing groundnut productivity. Appropriate planting geometry is expected to help enhance crop yield, water productivity, economic water productivity, and economic returns. Similarly, soil moisture content is a key factor in semi-arid tropics, affecting crop productivity. Evaluating soil moisture during the crop-growing season and up to the rooting depth is important for understanding its variation and impact on crops. Past studies measured landform management's effect on soil water content, but research on how paired row planting influences soil water in 0–30 cm layers is lacking (Hati et al., 2013; Pathak et al., 2011).

In SATs, there is a dearth of studies evaluating different planting geometries and addressing the issues of yield, water productivity, economic water productivity, and economic returns of groundnut. The authors hypothesized that appropriate planting geometry could be an efficient agronomic management strategy in landscapes of SATs and is expected to improve pod yield, water productivity, economic water productivity, and economic returns of groundnut. The evaluation of planting geometry using statistical models, such as the logistic growth model to study the growth pattern of above-ground biomass and leaf area index, Bayesian Posterior Probability indicating performance of planting geometry, and the random forest model to predict the pod yield under various planting geometries, was the novelty of the present study. The present field study was carried out with the specific objectives to: (1) To study the effect of paired row planting on pod yield, water productivity, and economic water productivity and (2) To identify an effective planting geometry/paired row system for groundnut, (3) To predict the pod yield through a Random Forest model using the above ground available data in different planting geometries y and 4) To study the economics of the experiment.

2. Materials and methods

2.1. Experimental site and soil characteristics

The field experiments were conducted at the RP4-A field of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad, India (Figure 1). The local climate of the study area is semi-arid, with an average annual rainfall of 895 mm and 75–80% of the total rainfall occurring during the wet season (June–October). Daily rainfall and maximum and minimum temperature data were collected from the Agrometeorology observatory at ICRISAT, near the experimental site, for the experimental period. The rainfall and temperature during the experimental period are shown in Figure 2. The maximum temperatures reached 41.2°C and 39.2°C, whereas the minimum temperatures were 7.6°C and 7°C during 2016–17 and 2017–18, respectively.

The soil at the experimental site was Alfisol. The soil samples from the experimental site were collected from 0 to 30 cm soil depth and analysed for initial physical and chemical properties. The initial soil texture analysis using a hydrometer (Klute & Page, 1986) showed 54.31% coarse sand, 28.12% fine sand, 13.41% silt, and 7.68% clay. Soil bulk density was determined using the core sampler method following the standard procedure described by Black (1965). and was 1.54 g cm^{-3}. The water-holding capacity at the field capacity and wilting point was analyzed using a pressure plate apparatus (Thorne & Peterson, 1954). The water-holding capacity at field capacity was 15.5% (0.03 MPa), and the wilting point was 8.65% (1.5 MPa). For chemical analysis, pH analysis was done with a glass electrode using a soil/water ratio of 1:2 (Jackson et al., 1973), electrical conductivity with an electrical conductivity meter using a soil/water ratio of 1:2 (Jackson et al., 1973), and organic carbon was analyzed following the Walkley-Black method (Naelson & Sommers, 1996). Available phosphorous (P), potassium (K), sulphur (S), boron (B), and zinc (Zn) were extracted using sodium bicarbonate for P (Olsen & Sommers, 1982), ammonium acetate for K (Helmke & Sparks, 2018), 1.5 g kg^{-1} calcium chloride for S (Tabatabai, 1996), hot water for B (Keren, 1996), and diethylenetriaminepentaacetic acid (DTPA) reagent for Zn (Lindsay & Norvell, 1978). Available P was determined by the colorimetric method, and K was determined by an Atomic Absorption Spectrophotometer (AAS). Analyses of S, B, and Zn were done using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES). Initial chemical analysis of soil sample showed, pH-7.89, EC-0.08 dS m^{-1}, organic carbon-0.31%, available nitrogen-142.40 kg ha^{-1}, phosphorous-22.62 kg ha^{-1}, potassium-176.96 kg ha^{-1} sulphur-6.92 ppm, and boron-0.47 ppm.

2.2. Field experimental details

A two-year field experiment was conducted during the post-monsoon seasons of 2016–2017 and 2017–2018 at the RP4-A research farm of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, to evaluate the effect of different planting geometries on pod yield, water productivity, and economic water productivity of two groundnut varieties, namely ICGV91114 and ICGV00351. This two-factor factorial experiment was laid out in a randomized block design set-up with three blocks to control field heterogeneity. Planting geometries and groundnut varieties were the two factors. Each plot measured 6 m × 22 m, with a 1.5 m border on each side. Five paired row plantings were: PR1 (20:20 cm / 40 cm) × 10 cm, PR2 (25:25 cm / 50 cm) × 10 cm, PR3 (20:20 cm / 25 cm) × 10 cm, PR4 (15:15 cm / 22.5 cm) × 10 cm, and PR5 30 cm × 10 cm (normal spacing). These were studied in two groundnut varieties, V1-ICGV91114 and V2-ICGV00351.

The spacing PR1- (20:20 cm/40 cm) × 10 cm indicates that the spacing between two inter-rows was 20 cm, the spacing between two paired rows was 40 cm, and the spacing between intra-row plants was 10 cm. Similarly, in the case of PR2- (25:25 cm / 50 cm) × 10 cm, PR3-

Figure 1. Field experiment site at ICRISAT, Hyderabad, India.

(20:20 cm / 25 cm) × 10 cm, and PR4- (15:15 cm / 22.5 cm) × 10 cm, the inter-row spacing was 25 cm, 20 cm, and 10 cm, respectively. The spacing between paired rows was 50 cm, 25 cm, and 22.5 cm, respectively, while the spacing between intra-row plants was 10 cm. The inter-row spacing in PR5- 30 cm × 10 cm (normal spacing) was 30 cm, with intra-row plant spacing of 10 cm. The number of plant rows was 4 in PR1, PR2, and PR5. PR3 had 5 plant rows, and PR4 had 6 planting rows in paired row planting.

Figure 2. Daily rainfall (mm), maximum (tmax), and minimum (tmin) temperature during the crop growing period (2016–17 and 2017–18) at the experimental site. Dates are presented as day-month-year.

The recommended macronutrients were applied, comprising 20, 40, and 60 kg N, P_2O_5, and K_2O per hectare, respectively. Additionally, zinc sulphate at 25 kg per hectare for zinc and borax at 10 kg per hectare for boron were used to meet micronutrient requirements. These fertilizers were applied as basal doses. The broad bed furrow system, consisting of a 120-cm wide bed with 30-cm wide and 15-cm deep furrows on either side, was created using a tractor-drawn broad bed furrow maker. During both years of the experimentation, the seeding rate was 150 kg per hectare for both groundnut varieties (ICGV91114 and ICGV00351). The field was maintained weed-free throughout the critical growth period (up to 45 days after sowing), and necessary plant protection measures were taken across all treatments to control insect attacks and diseases.

The groundnut were grown with seven irrigations using sprinklers in both 2016–17 and 2017–18. These irrigations were given according to the eight critical growth stages of groundnut. A total of 360 mm of water was supplied through these irrigations. The first irrigation of 30 mm was applied immediately after sowing to promote rapid, uniform germination. The second irrigation was at 13 DAS (vegetative stage), the third at 28 DAS (grand growth stage), the fourth at 38 DAS (pre-flowering), the fifth at 55 DAS (flowering stage), the sixth 74 DAS (pegging stage), the seventh at 103 DAS (pod and seed formation), and the eighth at 123 DAS, two days before harvest. Of these, 50 mm was applied at each of the second to sixth irrigations, while 30 mm was used for the final irrigation.

2.3. Field data collection

2.3.1. Soil moisture monitoring

Soil moisture content (SMC) was monitored up to 0.30 m soil depth in each planting geometry using a calibrated neutron probe (503DR Hydroprobe, CPN International, Concord, CA) at 20-day intervals (Wani etal, 1999). The neutron probe's source was lowered to 0.3 m soil depth with 0.15-m depth increments, and SMC was recorded at two depths. The SMC values at each 0.15-m soil depth were converted to volumetric water content and averaged over the 0–0.3 m soil depth. Standard deviation (σ) and standard error were calculated by the following equations:

$$\sigma = \sqrt{\frac{\sum (X - \bar{X})^2}{n - 1}}$$

$$Standarrd\ error = \frac{\sigma}{\sqrt{Number\ of\ values\ in\ the\ data\ set}}$$

where ∑ = add up
σ = standard deviation
X = Individual observations
$\bar{X}$ = average
n = number of observations

2.3.2. Pod yield

At maturity, the number of pods per plant in both groundnut varieties (ICGV91114 and ICGV00351) was recorded in each planting geometry. For yield estimation, the crop was harvested from an area of 9.0 m^2 in each plot, from three locations. Pods and haulms were separated, dried in an oven at 40–45°C with relative humidity less than 20%, and the weight of the pods per hectare was recorded.

2.3.3. Water productivity, net monetary returns, and economic water productivity

The water productivity (WP) of groundnut varieties in different paired row planting treatments was calculated by the following equation:

$$Water\ Productivity(kg\ m^{-3}) = \left(\frac{Pod\ yield(kg\ ha^{-1})}{Total\ Water\ Inputs(m^{-3}\ ha^{-1})}\right)$$

Total water inputs (TWI) include rainfall + irrigation in a hectare crop area.

The TWI was 3316 m3 during the first year and 3304 m3 during the second year of the experiment. The pod yield was estimated treatment-wise based on prevailing market rates, and gross monetary returns (USD ha^{-1}) were calculated by multiplying the values of produce and market rates USD kg^{-1}. Given the various inputs used in the present study, the cultivation cost (USD per hectare) was calculated by summing all costs for purchasing inputs, mechanical operations, and labor. Net monetary returns (USD per hectare) for both groundnut varieties were calculated by subtracting cultivation costs from the gross monetary returns for each treatment. The economic water productivity of groundnut varieties was calculated by the following equation:

$$\text{Economic Water Productivity}(\text{USD } m^{-3}) = \frac{Net\ monetary\ return(USD\ ha^{-1})}{Total\ Water\ Inputs(m^{-3}\ ha^{-1})}$$

where economic water productivity of groundnut is (USD m^{-3}), Net monetary returns (USD ha^{-1}) and TWIs is total water inputs (m^3 ha^{-1}), which includes rainfall + irrigation in a hectare crop area.

2.4. Statistical analyses

2.4.1. Comparison of effects of planting geometries and varieties

A two-way analysis of variance (ANOVA) model was fitted to test the effects of different planting geometries and varieties, and their interactions, on above-ground biomass and leaf area index, pod yield, water productivity, net monetary returns, and economic water productivity. Upon establishing statistical significance, treatment means were compared using Duncan's multiple range test (DMRT) at $\alpha = 0.05$ (Duncan, 1955).

2.4.2. Logistic growth model to study the growth pattern of above-ground biomass (AGB) and leaf area index (LAI) under different planting geometries

The logistic model is commonly used to describe sigmoidal growth patterns, especially in population dynamics, plant growth, and crop biomass accumulation (Costanza et al., 2025). To study the growth dynamics of AGB and LAI, we fitted a logistic growth model of the form,

$$Y(t) = \frac{K}{1 + e^{-r(t - t_0)}}$$

where Y(t) is the AGB or LAI at days after sowing (DAS) t, K is the carrying capacity, which measures the asymptotic maximum of AGB or LAI, r is the growth rate, and t_0 is the point of inflection (DAS) at which the growth changes its pace.

The logistic growth model was fitted to examine the dynamics of above-ground biomass (AGB) and leaf area index (LAI) across different planting geometries.

2.4.3. Bayesian posterior probability model

We extended our analysis using a Bayesian hierarchical posterior probability model to estimate the probability of achieving higher pod yield,WP, NMR, and EWP than under normal spacing for each planting geometry. The factor planting geometry was modeled as a fixed effect, and year and replication (nested within year) were included as random intercepts to account for experimental hierarchy. Informative priors assigned were Normal (0, 10) for fixed effects and Normal (0, 5) for random effects. Four Markov Chain Monte Carlo (MCMC) chains were run per model, each with 2000 iterations (including 1000 warm-up iterations). Convergence of posterior samples was assessed using the potential scale reduction factor ($\hat{R}$), with values below 1.00 indicating satisfactory convergence.

The posterior probability that a given planting geometry G1 performs better than normal spacing (G5), given the observed data, was derived as below:

$$P(\theta_{G1} > \theta_{G5}|data) = \frac{Number\ of\ posterior\ samples\ where\ \theta_{G1} > \theta_{G5}}{Total\ number\ of\ samples}$$

where, θ_{G1} and θ_{G5} be the estimated effects of geometry G1 and normal spacing (G5).

2.4.4. Random Forest model to predict pod yield under various planting geometries

Random Forest (RF), a machine learning-based algorithm, can be effective at capturing the non-linear yield pattern in response to changes in input data to accurately predict crop yield, compared to linear statistical models (Bons & Dhanoa, 2026; Haseeb et al., 2025; Hoffman et al., 2018). In the present study, the Random Forest model was employed to predict pod yield early in the season using available above-ground data. The response variable was pod yield. The dataset comprised five planting geometries, with LAI and AGB observations recorded at seven phenological stages (30, 45, 60, 75, 90, and 120 days after sowing). In addition, soil fertility variables, namely soil organic carbon, Phosphorus, Potassium, Calcium, Magnesium, Sulphur, Zinc, Iron, Boron, and weather variables such as minimum temperature, diurnal temperature range, solar radiation, and bright sunshine hours during different phenological stages were included as predictor variables. A separate RF regression model was trained using a sequential, stage-wise modeling approach for each growth stage and planting geometry. At each stage, the LAI and AGB values recorded up to that point were included as predictors, along with weather variables. For example, LAI and AGB at 30 DAS were used in the model for 30 DAS. As the crop progressed, observations from subsequent stages were incrementally added to the predictor set, enabling a more informed prediction of pod yield. At 30 DAS, the model incorporated LAI and AGB from both 15 and 30 DAS. This cumulative inclusion continued until 120 DAS, at which point LAI and AGB values from all 7 growth stages (15-120 DAS) were used. This progressive strategy facilitates real-time crop monitoring, enabling dynamic, geometry-specific yield potential assessment, capturing physiological growth patterns and environmental responses. This approach supports informed decision-making throughout the growing season for each planting geometry.

The observed pod yield from the field was compared with the model-predicted yield at each stage, and the model's prediction performance at each stage was assessed using the goodness-of-fit measure root mean square error (RMSE). This allowed us to assess how early yield can be reliably predicted from crop growth and environmental conditions, and which growth stages are most critical for accurate simulation.

2.5. Statistical software

All statistical analyses were conducted using R software (version 4.4.3; R Core Team, 2024). The 'agricolae' package was used to perform ANOVA and DMRT (Mendiburu, 2020). The Bayesian hierarchical posterior model was implemented using the 'brms' package (Bürkner, 2017). The RF model was fitted using the 'randomForest' package (Liaw & Wiener, 2002). All visualizations were created using the 'ggplot2' package (Wickham, 2025).

3. Results

3.1. Soil moisture content in different soil depths

The effect of paired row planting showed variation in soil moisture at 0–30 cm depth. In the first year, PR2 had the highest average moisture of 1.98 cm, and PR3 had the lowest soil moisture content (1.88 cm). Moisture ranged from 1.46 to 2.14 cm in PR3, 1.48–2.18 cm in PR4, 1.49–2.21 cm in PR5, 1.51–2.23 cm in PR1, and 1.55–2.28 cm in PR2. In the second year, a similar trend was recorded, with PR2 showing higher moisture levels by 1.61% compared to PR1, 2.97% compared to PR5, 4.14% compared to PR4, and 5.14% compared to PR3 (Figure 3).

3.2. Effect of paired row planting on groundnut pod yield and net monetary returns

The groundnut pod yield in the PR2 paired row system was higher (2202 and 2241 kg ha^{-1}) compared to other

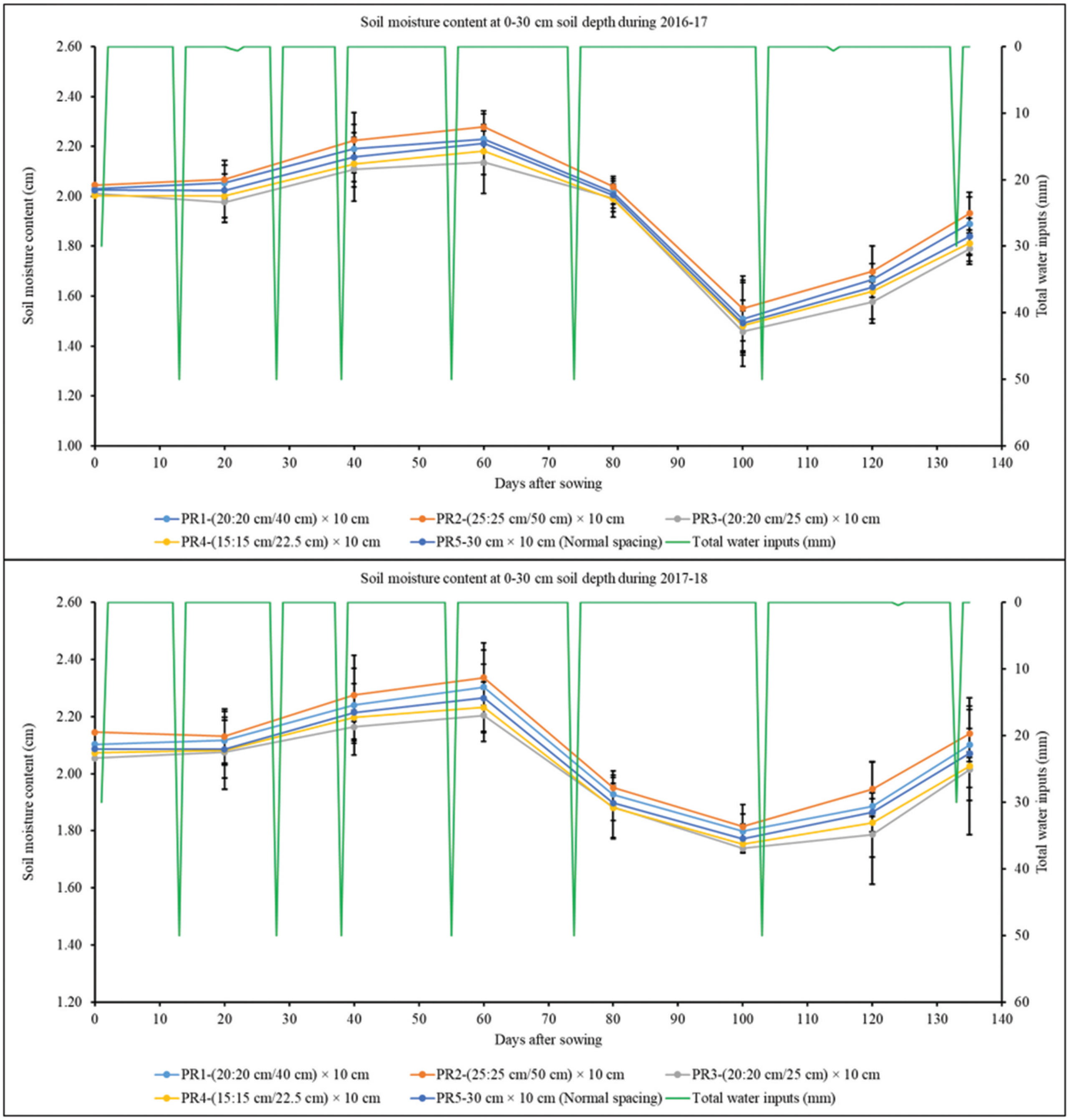

Figure 3. Soil moisture content (cm) in 0–30 cm soil depth of five paired rows during 2016–17 and 2017–18. The error bars indicate standard error.

paired row planting geometries, while the lowest pod yield was recorded in PR3 (1769 and 1810 kg ha^{-1}) during 2016–17 and 2018–19, respectively. The PR2 paired row increased groundnut pod yield by 25% and 24% over PR3 paired row planting in 2016–17 and 2017–18, respectively (Figure 4(a)).

The data indicate that the highest net monetary returns for groundnut were obtained with the PR2 paired row (1125 USD ha^{-1} in 2016–17 and 1141 USD ha^{-1} in 2017–18), while the PR3 paired row (843 USD ha^{-1} in 2016–17 and 861 USD ha^{-1} in 2017–18) recorded the lowest net monetary returns for groundnut (ICGV91114) (Figure 4(b)). The PR2 paired row increased net monetary returns by 34% and 33% over the PR3 paired row planting in 2016–17 and 2017–18, respectively (Figure 4(b)). The net monetary returns in both varieties remained the same, as equivalent pod yields were obtained. Both groundnut varieties (ICGV91114

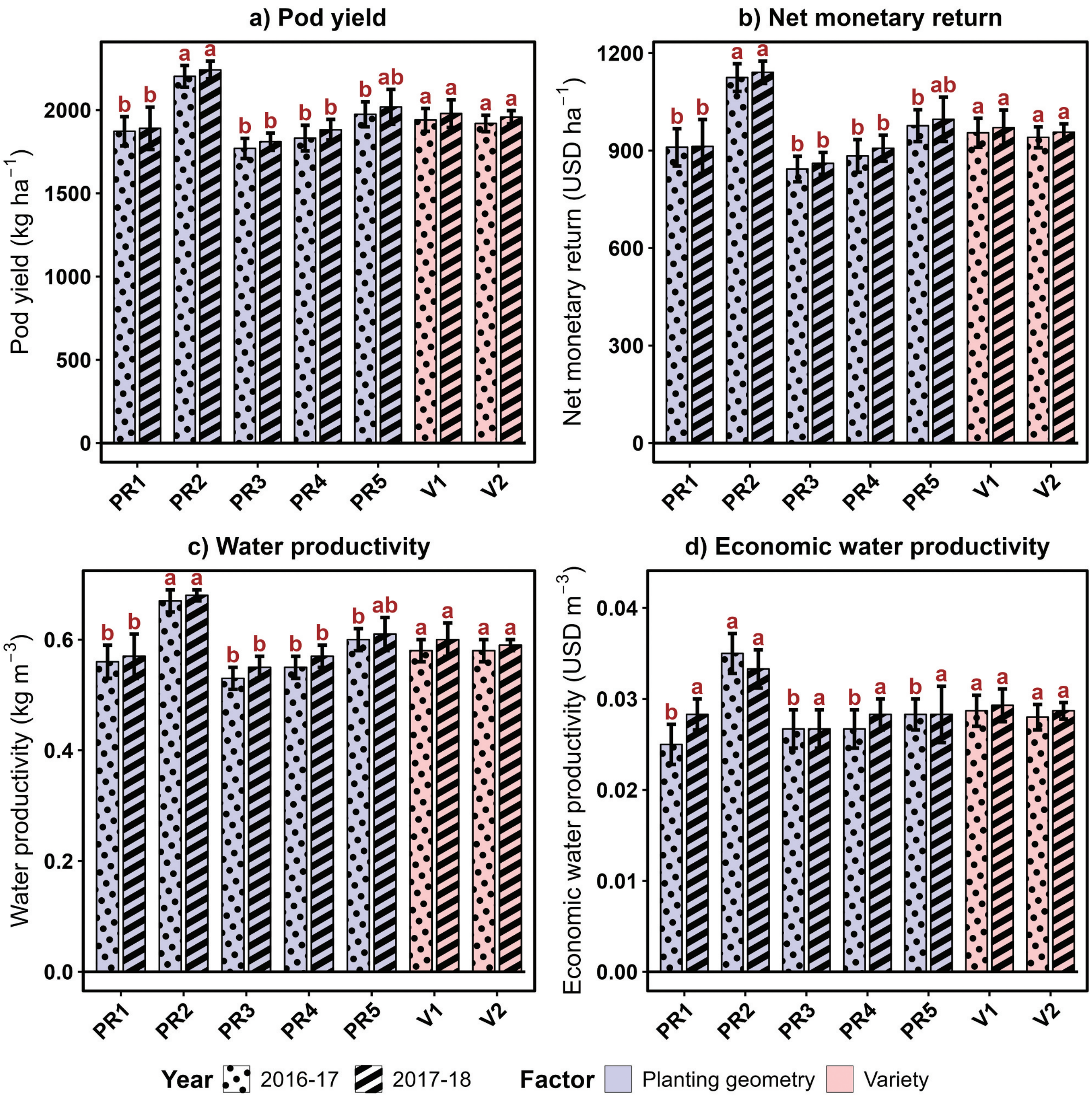

Figure 4. Effect of paired row planting and varieties on pod yield (kg ha^{-1}), water productivity (kg m^{-3}), net monetary return (USD ha^{-1}) and economic water productivity (kg m^{-3}) during 2016–17 and 2017–18. Treatments sharing the same letter were not significantly different, while different letters indicate significant differences in treatment means at α = 0.05 (DMRT). The letter 'a' denotes the highest mean group. PR1: (20:20 cm / 40 cm)×10 cm; PR2: (25:25 cm / 50 cm)×10 cm; PR3: (20:20 cm / 25 cm)×10 cm; PR4: (15:15 cm / 22.5 cm) × 10 cm; PR5: 30 cm × 10 cm (Normal spacing); V1: ICGV91114; V2:ICGV00351

and ICGV00351) showed slightly higher pod yields and net monetary returns in the second year (2017–18) compared to the first year (2016–17).

3.3. Effect of paired row planting on water productivity and economic water productivity

The effect of paired row planting treatments was significant on water productivity (Figure 4(c)) and economic water productivity (Figure 4(d)) of groundnut during 2016–17 and 2017–18. Among the paired rows, PR2 recorded the highest water productivity (0.67 kg m^{-3} in 2016–17 and 0.68 kg m^{-3} in 2017–18). Meanwhile, lower water productivity was recorded in PR3 (0.53 kg m^{-3} in 2016–17 and 0.55 kg m^{-3} in 2017–18) (Figure 4(c)). The PR2 paired row increased water productivity by 26% and 23% over PR3 paired row planting in 2016–17 and 2017–18, respectively (Figure 4(c)).

The economic water productivity was influenced by paired row planting in both years (Figure 4(d)). It was higher in PR2 paired row planting (0.035 USD m^{-3} in 2016–17 and 0.033 USD m^{-3} in 2017–18), while it was lowest in PR3 paired row planting during both years. Compared to PR3 paired row planting, the percentage increase in water productivity for PR2 was 30% in 2016–17 and 22% in 2017–18.

Pod yield, water productivity (WP), net monetary return (NMR), and economic water productivity (EWP) were significantly influenced by the interaction between variety and planting geometry across both seasons (Table 1). In 2016–17, the highest pod yield (2298 kg ha^{-1}) was recorded with ICGV 91,114 (V1) in PR2, which remained consistent in 2017–18 (2329 kg ha^{-1}), and was statistically superior to other treatments. ICGV 91,114 (V1) in PR2 also resulted in the maximum NMR (1187 and 1198 USD ha^{-1} in 2016–17 and 2017–18, respectively). ICGV 91,114 (V1) in PR2 recorded the highest EWP of 0.69 kg m^{-3} and 0.70 kg m^{-3} in 2016–17 and 2017–18, respectively. Water productivity was also higher with ICGV 00351 (V2) in PR2 (0.64 kgm^{-3} during 2016–17 and 0.65 kgm^{-3} during 2017–18). Conversely, lower pod yield and NMR were observed under ICGV 91,114 (V1) in PR3. Overall, ICGV 91,114 (V1) in PR2 consistently outperformed other combinations, highlighting its superiority for yield, profitability, and water-use efficiency.

3.4. Effect of paired row planting and varieties on growth parameters

The pooled analysis of leaf area index (LAI) and above-ground biomass (AGB) over two years showed significant differences across different paired row plantings and varieties at various crop growth stages (Table 2). There was no notable difference in LAI among paired row plantings at 15 DAS, but significant differences appeared from 30 DAS onward ($p < 0.01$). The paired row planting PR2 consistently performed better than other paired row plantings throughout all growth stages. PR3 had comparatively lower LAI values. The effects of varieties were minimal at 15 DAS but became highly significant afterward. Variety ICGV00351 (V2) showed higher LAI values compared to ICGV91114 (V1) across all stages.

In the case of AGB, paired row planting and variety had a significant effect ($p < 0.01$). PR2 produced the highest biomass accumulation throughout the growing period, while PR3 recorded the lowest above-ground biomass accumulation throughout the growing period (Table 2). Among the varieties, ICGV91114 (V1) produced more above-ground biomass up to 45 DAS; however, from 60 DAS onwards, ICGV00351 (V2) had higher above-ground biomass than ICGV91114 (V1). These results indicate that paired row planting (PR2) was

Table 1. Interaction effect of planting geometry and variety on pod yield (kg ha^{-1}), water productivity (kg m^{-3}), net monetary return (USD ha^{-1}), and economic water productivity (kg m^{-3}) during 2016–17 and 2017–18.

Treatment	Pod yield (kg ha^{-1})	Water Productivity (kg m^{-3})	Net monetary return (USD ha^{-1})	Economic Water Productivity (USD m^{-3})
2016–17				
V1 × PR1	1776 ± 119^{bc}	0.53 ± 0.04^{bc}	848 ± 77^{bc}	0.023 ± 0.003^{b}
V1 × PR2	2298 ± 57^{a}	0.69 ± 0.02^{a}	1187 ± 37^{a}	0.037 ± 0.003^{a}
V1 × PR3	1749 ± 77^{c}	0.53 ± 0.02^{c}	830 ± 50^{c}	0.027 ± 0.003^{b}
V1 × PR4	1844 ± 151^{bc}	0.56 ± 0.04^{bc}	891 ± 98^{bc}	0.027 ± 0.003^{b}
V1 × PR5	2038 ± 117^{abc}	0.61 ± 0.03^{abc}	1017 ± 76^{abc}	0.030 ± 0^{ab}
V2 × PR1	1969 ± 124^{bc}	0.59 ± 0.04^{bc}	972 ± 81^{bc}	0.027 ± 0.003^{b}
V2 × PR2	2107 ± 94^{ab}	0.64 ± 0.04^{ab}	1062 ± 61^{ab}	0.033 ± 0.003^{ab}
V2 × PR3	1791 ± 110^{bc}	0.54 ± 0.04^{bc}	857 ± 71^{bc}	0.027 ± 0.003^{b}
V2 × PR4	1820 ± 83^{bc}	0.55 ± 0.04^{bc}	876 ± 54^{bc}	0.027 ± 0.003^{b}
V2 × PR5	1912 ± 103^{bc}	0.58 ± 0.03^{bc}	936 ± 67^{bc}	0.027 ± 0.003^{b}
p-value	0.03	0.03	0.01	0.05
CV (%)	9.13	9.09	12.09	0.00
2017–18				
V1 × PR1	1797 ± 265^{b}	0.54 ± 0.08^{b}	852 ± 173^{b}	0.027 ± 0.006^{b}
V1 × PR2	2329 ± 74^{a}	0.70 ± 0.02^{a}	1198 ± 48^{a}	0.037 ± 0.003^{a}
V1 × PR3	1795 ± 106^{b}	0.54 ± 0.03^{b}	851 ± 69^{b}	0.027 ± 0.003^{b}
V1 × PR4	1891 ± 124^{b}	0.57 ± 0.04^{b}	913 ± 80^{b}	0.027 ± 0.003^{b}
V1 × PR5	2085 ± 190^{ab}	0.63 ± 0.06^{ab}	1039 ± 123^{ab}	0.030 ± 0.006^{ab}
V2 × PR1	1984 ± 41^{ab}	0.60 ± 0.01^{ab}	974 ± 27^{ab}	0.030 ± 0^{ab}
V2 × PR2	2154 ± 32^{ab}	0.65 ± 0.01^{ab}	1084 ± 21^{ab}	0.030 ± 0^{ab}
V2 × PR3	1825 ± 43^{b}	0.55 ± 0.01^{b}	871 ± 28^{b}	0.027 ± 0.003^{b}
V2 × PR4	1873 ± 61^{b}	0.57 ± 0.02^{b}	901 ± 40^{b}	0.030 ± 0^{ab}
V2 × PR5	1953 ± 121^{ab}	0.59 ± 0.03^{ab}	953 ± 79^{ab}	0.027 ± 0.003^{b}
p-value	0.05	0.05	0.05	0.05
CV (%)	10.97	10.88	14.57	0.00

Treatments sharing the same letter were not significantly different, while different letters indicate significant differences in treatment means at α = 0.05 (DMRT). The letter 'a' denotes the highest mean group.

PR1: (20:20 cm / 40 cm)×10 cm; PR2: (25:25 cm / 50 cm)×10 cm; PR3: (20:20 cm / 25 cm)×10 cm; PR4: (15:15 cm / 22.5 cm) × 10 cm; PR5: 30 cm × 10 cm (Normal spacing); V1: ICGV91114; V2:ICGV00351.

Table 2. Effect of paired row planting and varieties on time series leaf area index and above-ground biomass pooled over two years (2016–17 and 2017–18).

Trt	15 DAS	30 DAS	45 DAS	60 DAS	75 DAS	90 DAS	120 DAS
Leaf area index (Mean±SE)							
Paired row planting							
PR1	0.27 ± 0.01[a]	0.61 ± 0.02[ab]	1.28 ± 0.06[b]	1.75 ± 0.02[b]	1.99 ± 0.04[b]	2.33 ± 0.09[b]	2.41 ± 0.11[b]
PR2	0.27 ± 0.01[a]	0.64 ± 0.02[a]	1.43 ± 0.06[a]	1.97 ± 0.03[a]	2.21 ± 0.06[a]	2.52 ± 0.11[a]	2.60 ± 0.12[a]
PR3	0.26 ± 0.01[a]	0.53 ± 0.03[c]	1.04 ± 0.05[e]	1.42 ± 0.02[e]	1.63 ± 0.06[e]	1.87 ± 0.07[e]	1.93 ± 0.08[e]
PR4	0.25 ± 0.01[a]	0.56 ± 0.04[c]	1.13 ± 0.07[d]	1.54 ± 0.05[d]	1.75 ± 0.05[d]	2.00 ± 0.08[d]	2.09 ± 0.09[d]
PR5	0.25 ± 0.01[a]	0.57 ± 0.02[bc]	1.19 ± 0.06[c]	1.64 ± 0.03[c]	1.84 ± 0.04[c]	2.15 ± 0.09[c]	2.23 ± 0.09[c]
p-value	0.53	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Variety							
V1	0.26 ± 0[a]	0.53 ± 0.02[b]	1.08 ± 0.04[b]	1.61 ± 0.05[b]	1.78 ± 0.05[b]	1.99 ± 0.06[b]	2.05 ± 0.06b
V2	0.26 ± 0[a]	0.64 ± 0.01[a]	1.34 ± 0.04[a]	1.71 ± 0.05[a]	1.99 ± 0.06[a]	2.36 ± 0.07[a]	2.46 ± 0.07a
p-value	0.92	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CV (%)	7.71	6.41	2.97	3.35	2.54	3.96	3.14
Above Ground Biomass (Mean±SE)							
Paired row planting							
PR1	131 ± 9[b]	284 ± 8[b]	883 ± 26[b]	1692 ± 18[b]	3360 ± 79[b]	5558 ± 156[b]	7603 ± 521a
PR2	138 ± 7[a]	305 ± 3[a]	985 ± 30[a]	1897 ± 19[a]	3752 ± 70[a]	6033 ± 148[a]	7695 ± 680[a]
PR3	119 ± 9[c]	252 ± 11[d]	702 ± 13[e]	1347 ± 35[e]	2798 ± 75[e]	4842 ± 213[e]	6724 ± 558[d]
PR4	121 ± 10[c]	258 ± 11[cd]	758 ± 18[d]	1449 ± 24[d]	2942 ± 73[d]	5039 ± 188[d]	6979 ± 506[c]
PR5	125 ± 10[bc]	262 ± 9[c]	851 ± 42[c]	1561 ± 22[c]	3123 ± 88[c]	5293 ± 170[c]	7216 ± 553[b]
p-value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Variety							
V1	147 ± 2[a]	290 ± 4[a]	891 ± 31[a]	1545 ± 56[b]	3034 ± 92[b]	4971 ± 127[b]	5990 ± 95[b]
V2	107 ± 3[b]	255 ± 7[b]	781 ± 24[b]	1633 ± 47[a]	3356 ± 90[a]	5736 ± 100[a]	8497 ± 124[a]
p-value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CV (%)	4.93	2.43	2.62	2.09	2.45	1.71	2.07

Treatments sharing the same letter were not significantly different, while different letters indicate significant differences in treatment means at α = 0.05 (DMRT). The letter 'a' denotes the highest mean group.

PR1: (20:20 cm/40 cm)×10 cm; PR2: (25:25 cm/50 cm)×10 cm; PR3: (20:20 cm/25 cm)×10 cm; PR4: (15:15 cm/22.5 cm)×10 cm; PR5: 30 cm × 10 cm (Normal spacing); V1: ICGV91114; V2:ICGV00351.

superior in terms of higher LAI and above-ground biomass production.

Leaf area index increased progressively with crop growth from 15 to 120 DAS across all treatment combinations (Figure 5). The differences among treatments were minimal, with LAI values below 0.5 during initial stages (15–30 DAS). From 45 DAS onward, significant variation emerged among treatments, with distinct groupings indicated by the letters above the error bars. ICGV00351 (V2) performed better with all planting geometries than ICGV91114 (V1) over all the growth stages.

The LAI increased sharply during 30–60 DAS, reaching values between 0.5 and 2.0. Particularly, ICGV00351 (V2) in PR2, PR1 and PR5 showed significantly better performance. In contrast, ICGV91114 (V1) in PR3 and PR4 exhibited relatively lower LAI during this period. The LAI under ICGV91114 (V1) in PR2 was close to ICGV00351 (V2) in PR2 at 60 DAS.

The ICGV00351 (V2) in PR2 showed the highest values (>2.7 at 120 DAS), followed by ICGV00351 (V2) in PR1 and PR5, suggesting that variety ICGV00351 under optimized planting geometries sustained greater canopy expansion. However, the treatment combinations involving V1 (especially V1 × PR1) maintained the lowest LAI (<1.75 at 120 DAS).

Overall, the variety ICGV00351 in association with PR2- (25:25 cm/50 cm)×12 cm, PR1- (20:20 cm/40 cm)×15 cm and PR5- 30 cm × 10 cm (Normal spacing) geometries promoted higher and sustained LAI throughout crop growth.

Above-ground biomass (AGB) increased steadily with crop growth from 15 to 120 DAS, showing distinct treatment effects at later stages (Figure 6). At early stages (15–30 DAS), biomass values were low (<500 kg ha^{-1}) and treatment differences were negligible.

From 45 DAS onward, treatment differences became more pronounced. ICGV00351 (V2) produced more biomass than ICGV91114 (V1) across planting geometries. Notably, ICGV00351 (V2) combined with PR2, PR1, and PR5 showed greater biomass accumulation. In contrast, ICGV91114 (V1) in PR3 and PR4 recorded lower biomass. After 90 DAS, the biomass production in ICGV91114 (V1) lagged across the gremtries than ICGV00351 (V2).

At physiological maturity (120 DAS), the highest AGB was observed in ICGV00351 (V2) under PR2 (>9000 kg ha^{-1}), followed by V2 × PR1 and V2 × PR5 (around 8500 kg ha^{-1}). The lowest biomass accumulation was recorded with ICGV91114 (V1) in PR3 and PR4. Overall, biomass accumulation patterns paralleled with LAI trends, reinforcing the positive role of variety ICGV00351 in optimized planting geometry PR2- (25:25

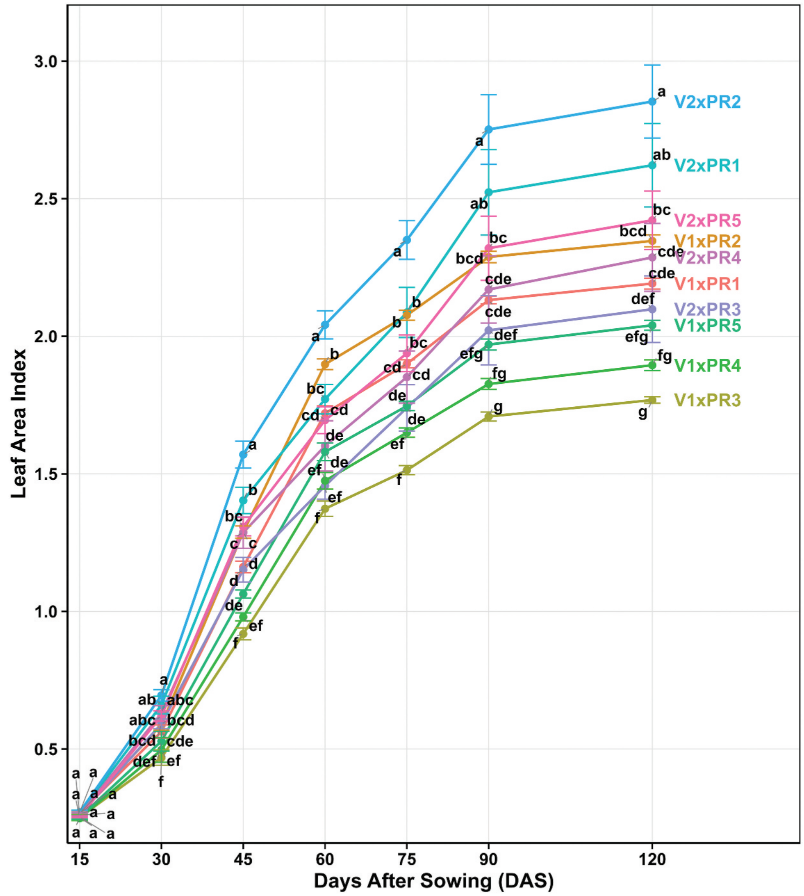

Figure 5. Interaction effect of paired row planting and varieties on time series leaf area index pooled over two years (2016–17 and 2017–18). Treatments sharing the same letter were not significantly different, while different letters indicate significant differences in treatment means at α = 0.05 (DMRT). The letter 'a' denotes the highest mean group. PR1: (20:20 cm/40 cm)×10 cm; PR2: (25:25 cm/50 cm)×10 cm; PR3: (20:20 cm/25 cm)×10 cm; PR4: (15:15 cm/22.5 cm)×10 cm; PR5: 30 cm × 10 cm (Normal spacing); V1: ICGV91114; V2: ICGV00351

cm/50 cm)×10 cm followed by PR1- (20:20 cm/40 cm)×10 cm and PR5- 30 cm × 10 cm (Normal spacing) produced more vigorous growth and biomass.

3.5. *Likelihood of superior performance of different paired row planting over normal spacing using Bayesian posterior probability model*

The Bayesian posterior probability model was used to evaluate the probability of superior performance from different planting geometries (PR1 to PR4) over the reference geometry, as normal spacing (PR5). The results indicated that planting geometries (PR1 to PR4) performed better compared to the normal spacing (PR5) pertaining to pod yield, water productivity (WP), net monetary return (NMR), and economic water productivity (EWP) (Figure 7).

Bayesian Posterior Probability indicated that pod yield was higher in paired row planting (PR2:20:20 cm/40 cm ×10 cm), which was 0.73 over PR5:30 cm × 10 cm (Normal spacing). This provides strong evidence of a significant enhancement under PR2. PR1 (20:20 cm/40 cm)×10 cm also demonstrated a moderate probability (0.44), suggesting it was likely beneficial for yield improvement. However, PR3 and PR4 had lower probabilities, implying a limited or uncertain yield advantage over PR5. The paired row planting (PR2) exhibited a high posterior probability (0.81), indicating strong support for higher monetary return compared to PR5, followed by PR1 (0.41).

Paired row planting PR2 showed a certain improvement over normal spacing (PR5) with a probability value of one in terms of water productivity and economic water productivity. The water productivity and economic water productivity from other paired-row plantings were not substantially higher than those with normal spacing, indicating little to no advantage over normal spacing. It can be summarised that paired row planting (PR2) consistently performed as the most effective paired row planting across all four parameters with

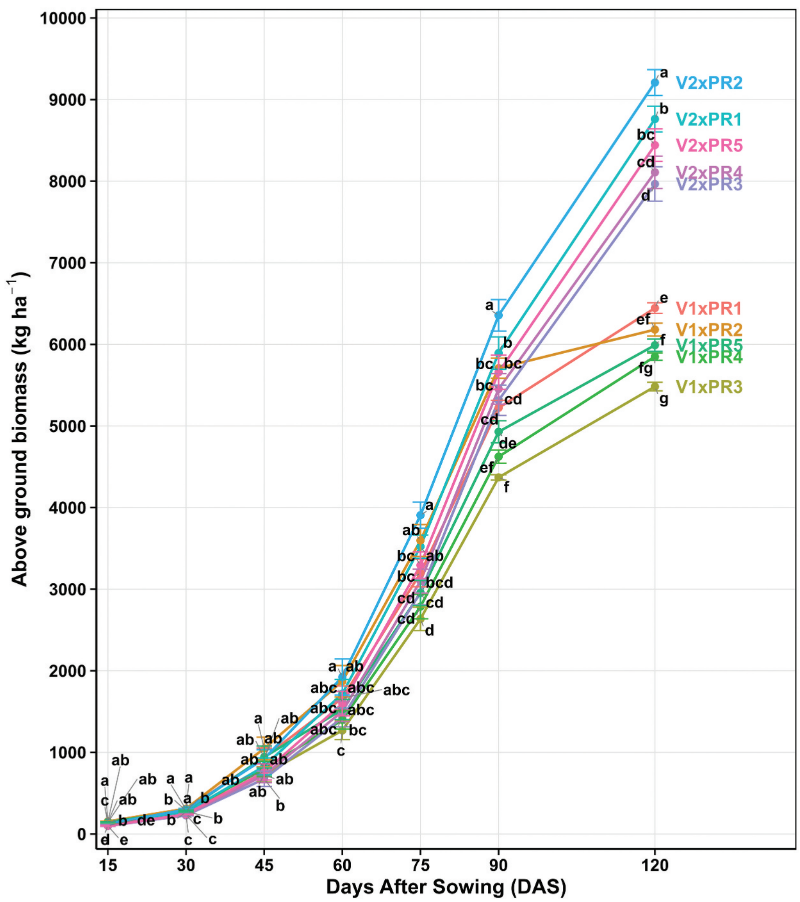

Figure 6. Interaction effect of paired row planting and varieties on time series above-ground biomass (kg ha^{-1}) pooled over two years (2016–17 and 2017–18). Treatments sharing the same letter were not significantly different, while different letters indicate significant differences in treatment means at α = 0.05 (DMRT). The letter 'a' denotes the highest mean group. PR1: (20:20 cm / 40 cm)×10 cm; PR2: (25:25 cm / 50 cm)×10 cm; PR3: (20:20 cm / 25 cm)×10 cm; PR4: (15:15 cm / 22.5 cm) × 10 cm; PR5: 30 cm × 10 cm (Normal spacing); V1: ICGV91114; V2:ICGV00351

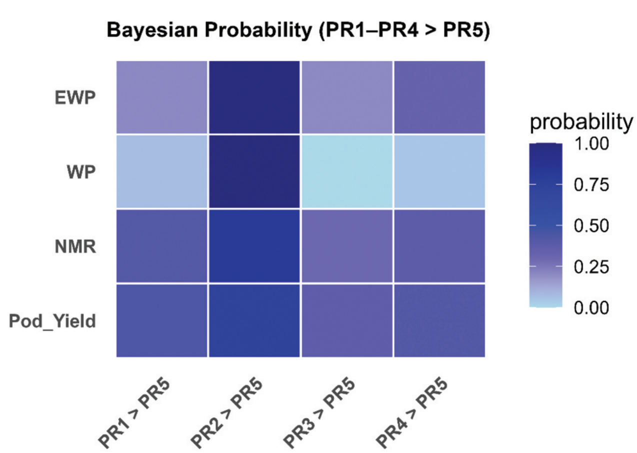

Figure 7. Bayesian posterior probability indicating performance of paired row planting (PR1 to PR4) over normal spacing (PR5) pertaining to pod yield, water productivity (WP), net monetary return (NMR), and economic water productivity (EWP). PR1: (20:20 cm / 40 cm)×10 cm; PR2: (25:25 cm / 50 cm)×10 cm; PR3: (20:20 cm / 25 cm)×10 cm; PR4: (15:15 cm / 22.5 cm) × 10 cm; PR5: 30 cm × 10 cm (Normal spacing).

respect to pod yield, monetary returns, water productivity, and economic water productivity. The PR1 showed a moderate potential, particularly for yield and net returns. The PR3 and PR4 offered limited and inconsistent advantages over the normal spacing.

3.6. Trade-off between pod yield and net monetary return for two groundnut varieties, ICGV91114 and ICGV00351, under different paired row planting

The bivariate plot shows a strong positive linear relationship: higher pod yields are associated with higher monetary returns (Figure 8). The plot is divided into four quadrants at the average pod yield of 1950 kg ha^{-1} and net return of 960 USD ha^{-1}, helping to distinguish high- and low-performing treatment combinations (Figure 8). Most of the data points of paired row plantings [(PR2-25:25 cm/50 cm) ×10 cm], [(PR1-20:20 cm/40 cm) ×10 cm], and [(PR3-20:20 cm/25 cm) ×10 cm] fall in the top-right quadrant, indicating

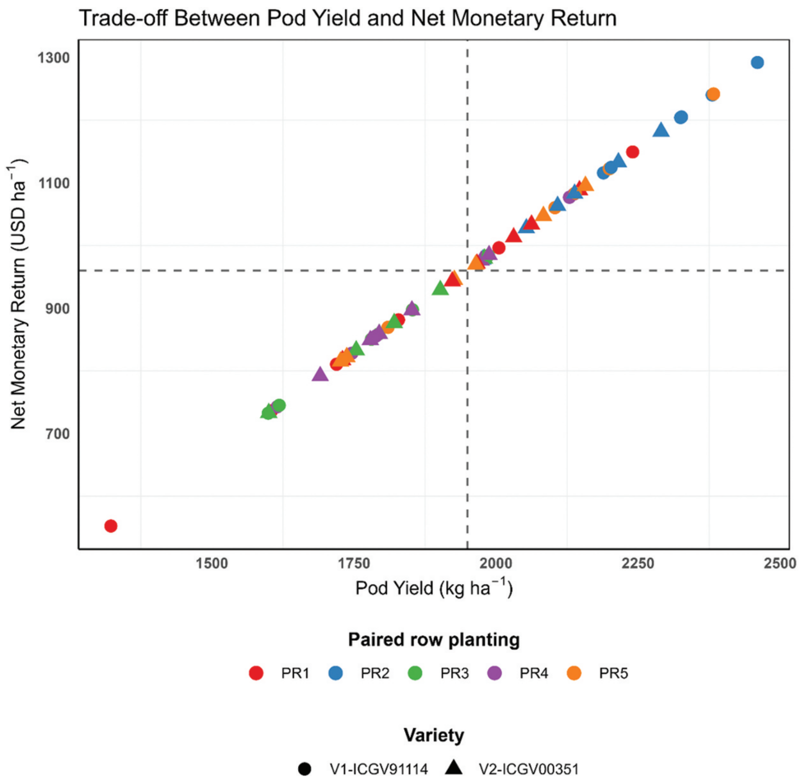

Figure 8. Bivariate plot illustrates the trade-off between pod yield and net monetary return for two groundnut varieties, ICGV91114 (solid circle) and ICGV00351 (triangle), under different paired row plantings. PR1: (20:20 cm / 40 cm)×10 cm; PR2: (25:25 cm / 50 cm)×10 cm; PR3: (20:20 cm / 25 cm)×10 cm; PR4: (15:15 cm / 22.5 cm) × 10 cm; PR5: 30 cm × 10 cm (Normal spacing).

high yield and high return, particularly when paired with the ICGV91114 variety. PR5 (Normal spacing) was clustered in the lower left with the central zone, suggesting relatively lower productivity and profitability. Furthermore, ICGV91114 consistently outperformed ICGV00351 across geometries, indicating its superior pod yield and economic potential. Overall, the results highlighted that paired row planting [(PR2-25:25 cm/50 cm) ×10 cm], [(PR1-20:20 cm/40 cm) ×10 cm] and [(PR3-20:20 cm/25 cm) ×10 cm], especially when combined with ICGV91114, offered the most promising strategy for maximizing both yield and net returns in groundnut.

3.7. Growth rate in above-ground biomass and leaf area index under different planting geometries

The growth dynamics of above-ground biomass and leaf area index across different paired row plantings were studied using the logistic growth model.

The parameter point of inflection (t_0) represents the DAS at which the growth shift was found to occur earlier for LAI (around 45 DAS) compared to AGB (ranging from 77 to 82 DAS), which confirmed that canopy expansion precedes peak biomass accumulation (Table 3). The model outcome revealed a distinct pattern in crop development dynamics across the paired row plantings. The PR2 (25:25 cm/50 cm)×10 cm) spacing exhibited the earliest AGB inflection (77 DAS) and the highest maximum biomass (8285 kg ha^{-1}), coupled with the highest overall growth rate (79 kg ha^{-1} day^{-1}). It also recorded the highest LAI potential (2.57), confirming a well-developed canopy supporting robust biomass growth. The paired row planting PR1 (20/40) also exhibited a similar pattern, but there was a delay of two days for inflection. The growth rate before inflection was 3 kg ha–1 day–1 lower than PR2, and it increased post-inflection. The PR5 (normal spacing- 30 cm × 10 cm) performed moderately, achieving reasonable biomass and LAI levels. In contrast, narrower spacings such as PR3- (20:20 cm/25 cm)×10 cm and PR4- (15:15 cm/22.5 cm)× 10 cm showed delayed biomass accumulation, lower growth rates in both pre- and post-inflection phases, and reduced maximum values for both AGB and LAI, which is likely due to competition or shade effects. Overall, the PR2-(25:25 cm/50 cm)×10 cm planting geometry was the most efficient, supporting early canopy development and biomass accumulation and optimizing growth.

Table 3. Logistic growth model to study the growth dynamics in above-ground biomass (AGB) and leaf area index (LAI) under different planting geometries.

	Above-ground biomass					Leaf area index				
Planting Geometry	Point of inflection (t_0) (Days after sowing)	Pre-inflection growth rate (kg ha^{-1} da^{-1})	Post-inflection growth rate (kg ha^{-1} da^{-1})	Overall growth rate (kg ha^{-1} da^{-1})	Asymptotic maximum value (K) (kg ha^{-1})	Point of inflection (t_0) (Days after sowing)	Pre-inflection growth rate	Post-inflection growth rate	Overall growth rate	Asymptotic maximum value (K)
PR1	79	61	88	77	8130	45	0.03	0.02	0.02	2.40
PR2	77	64	87	79	8285	44	0.03	0.02	0.02	2.57
PR3	82	54	84	71	7468	44	0.02	0.01	0.02	1.94
PR4	81	55	83	72	7556	44	0.03	0.01	0.02	2.08
PR5	81	58	87	76	7959	45	0.03	0.01	0.02	2.22

PR1: (20:20 cm / 40 cm)×10 cm; PR2: (25:25 cm / 50 cm)×10 cm; PR3: (20:20 cm / 25 cm)×10 cm; PR4: (15:15 cm / 22.5 cm) × 10 cm; PR5: 30 cm × 10 cm (Normal spacing).
Point of Inflection (t_0): This is the DAS when the growth rate shifts from accelerating or decelerating.
Pre-inflection growth rate: Average daily growth rate of AGB or LAI before the inflection point.
Post-inflection growth rate: Average daily growth rate of AGB or LAI after the point of inflection.
Overall growth rate: Average daily growth rate from 15 to 120 DAS.
Asymptotic maximum value (K): The theoretical maximum AGB or LAI as time progresses.

3.8. *Random Forest model for early prediction of pod yield during various growth stages under different planting geometries*

A machine learning-based framework using the Random Forest algorithm was employed to model crop growth dynamics and pod yield under varying paired row planting.

The crop-stage-wise Random Forest model prediction error for pod yield across five paired-row plantings showed a clear trend of decreasing error with crop maturity, suggesting that prediction models become more accurate as more physiological and canopy information becomes available over time (Table 4). Compared to other planting geometries, a significantly lower error was obtained in PR2 (25:25 cm/50 cm) ×10 cm even in early stages, where prediction is typically challenging. The PR2 [(25:25 cm/50 cm) ×10 cm] consistently showed the lowest prediction errors across all stages from 89 kg ha^{-1} at 30 DAS to 66 kg ha^{-1} from 75 DAS onward. In contrast, PR1 and PR5 showed persistently high errors, indicating less reliable yield forecasts. The PR3 also performed well, followed by PR2. Data, especially post-60 DAS, significantly enhanced prediction accuracy across the paired row plantings. The paired row planting (PR2) enabled more accurate, stable yield prediction using LAI, AGB, soil, and weather parameters through improved model calibration. Hence, groundnut pod yield can be predicted with greater accuracy from 75 DAS onwards using the fitted Random Forest model with the available above-ground data.

4. Discussion

The paired row planting directly influences soil moisture content. The higher soil moisture content in PR2 (25:25 cm/50 cm × 10 cm) paired row planting could be due to the larger space of 50 cm between two pairs of plant rows. This larger spacing in PR2 may have allowed better water infiltration and more even distribution within the soil profile. Water movement horizontally might also be more because of the increased space of 50 cm between the paired rows.

The greater gap in PR2 could promote better growth since resources like space, light, nutrients, and soil water are more available, leading to increased leaf area. The larger leaf area enhances the canopy shading of groundnut plants and may reduce direct solar radiation hitting the soil surface, which in turn lowers soil temperature and moisture loss through evaporation in the PR2 paired row treatment. Hsiao and Xu (2005) reported that soil temperature was reduced due to crop canopy coverage, which decreased solar radiation on the soil surface and helped conserve soil water. Additionally, increased canopy coverage lowers the throughfall and the impact of sprinkler water droplets on the soil surface. This diminishes the direct drop of water from sprinklers on

Table 4. Crop stages-wise prediction error (kg ha^{-1}) to predict pod yield under five planting geometries.

Paired row planting	30 DAS	45 DAS	60 DAS	75 DAS	90 DAS	120 DAS
PR1: (20:20 cm/40 cm) ×10 cm	197	161	154	137	130	129
PR2: (25:25 cm/50 cm) ×10 cm	89	78	70	66	67	67
PR3: (20:20 cm/25 cm) ×10 cm	92	76	74	71	67	71
PR4: (15:15 cm/22.5 cm) ×10 cm	123	99	97	96	95	91
PR5: Normal spacing 30 cm × 10 cm	179	143	134	134	134	130

the soil, allowing droplets to stay longer on the plant canopy. This slow trickle-down through leaf drips and stem flow contributes to better water infiltration within the soil profile (0–30 cm). Consequently, less evaporation and more water infiltration due to canopy shading resulted in higher soil water content in PR2 compared to other paired row treatments. Similar findings of increased infiltration and reduced evaporative losses have been reported in various studies (Ghanbari et al., 2010; Walker & Ogindo, 2003).

The spacing between the paired rows was smaller in PR3 (20:20 cm/25 cm × 10 cm) at 25 cm, and in PR4 (15:15 cm/22.5 cm × 10 cm) at 22.5 cm. This compact spacing did not allow for adequate water distribution during irrigation. Furthermore, having an additional fifth crop row in PR3 and a sixth row in PR4 could have increased competition among the plants for the limited water available, negatively affecting crop growth and development. Therefore, the closer spacing in PR3 and PR4 resulted in lower soil moisture across the soil profile (0–30 cm). Overall, the results suggest that paired row planting using four crop rows can improve soil moisture content within the soil profile.

PR2 planting geometry was found to be the most efficient configuration for higher leaf area index (LAI) and above-ground biomass (AGB), as confirmed by the logistic growth model. As a result, higher pod yield can be obtained in PR2 due to accelerated canopy development, biomass accumulation, and optimizing growth through enhanced photosynthetic activity, and better availability of soil moisture and nutrients throughout the season (Figure 3). Adequate soil moisture supported nutrient uptake and physiological processes such as membrane integrity, resulting in improved biomass accumulation and pod yield (Cakmak et al., 1995; Sadeghzadeh & Rengel, 2011). These findings align with recent reports that optimized crop management enhances groundnut productivity under water-limited conditions. Meena et al. (2025) reported maximum water productivity at 80% deficit irrigation in arid regions, while Shamsuddeen and Bashir (2025) observed significant yield gains with phosphorus application and mulching in the Nigeria savanna. Together, these results highlight that planting geometry, water management, and nutrient strategies can synergistically improve yield and sustainability in semi-arid ecosystems.

The paired row planting PR2 can be adopted for superior performance compared to normal spacing, as it consistently demonstrated a higher likelihood of achieving better pod yield and monetary return. There is also certainty in higher WP and EWP.

Further, PR2 stands out as the most reliable option for early and precise yield prediction, aiding timely and informed farm decisions. This advantage is likely attributed to its optimal spatial arrangement, which supports uniform crop growth.

In contrast, PR3 showed lower pod yield, water productivity, and economic water productivity, likely due to the soil's inability to meet the water and nutrient demands of the denser plant population. This observation is consistent with Sunil Kumar et al. (2021), who found that higher plant density with limited phosphorus reduced yield attributes and pod yield because of nutrient competition. Overall, the consistent superiority of PR2 in both years demonstrates that appropriate planting geometry optimizes the use of soil moisture and nutrients, thereby enhancing pod yield, profitability, and water-use efficiency. Comparable improvements in paired-row groundnut systems have been reported by Mandal, et al. (2019), who attributed yield gains to improved light interception and reduced unproductive evapotranspiration. Similar conclusions were drawn by Harisudan and Subrahmaniyan (2013), who found that plant geometry under drip irrigation significantly influenced yield and water productivity, with closer spacing restricting resource uptake.

5. Conclusions

Study demonstrated that planting geometry significantly influences soil moisture, crop growth, yield, water productivity, and profitability of post-rainy season groundnut under semi-arid tropical conditions. Across two consecutive seasons (2016–17 and 2017–18), the paired-row planting geometry PR2 [(25:25 cm/50 cm) × 10 cm] consistently outperformed the other planting systems and normal spacing under broad bed furrow cultivation. The PR2 maintained higher soil moisture in the 0–30 cm soil layer and promoted greater leaf area development, biomass accumulation, pod yield, water productivity, net monetary return, and economic water productivity. Among the two varieties, ICGV00351 showed better overall growth performance, although the variety × geometry interaction indicated that ICGV91114 under PR2 achieved the highest values for pod yield, water productivity, and economic returns across both years.

The superiority of PR2 was further supported by statistical modeling. The logistic growth model showed that PR2 promoted earlier and more efficient canopy development and biomass accumulation, while Bayesian posterior probability analysis confirmed its greater likelihood of outperforming normal spacing for yield, profitability, and water-use efficiency. The Random

Forest model also showed lower prediction error under PR2, indicating greater stability and improved predictability of pod yield. Overall, these findings identify PR2 [(25:25 cm/50 cm) × 10 cm] as a robust and climate-smart planting geometry for groundnut in the semi-arid tropics, with strong potential to improve productivity, water-use efficiency, and farm profitability under conditions of increasing water scarcity and climate variability. Future work should focus on developing scale-appropriate mechanization options for paired-row sowing, and refining predictive modelling tools could accelerate on-farm adoption and support decision-making for resilient groundnut production systems.

Author contributions

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Data availability statement

The data that support the findings of this study are available from the corresponding author, [Gajanan Sawargaonkar], upon reasonable request.

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