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Evaluation of Drip Supplemental Irrigation against Rainfall Deficits: Effects on the Phenology and Yield of Cotton (*Gossypium hirsutum* L.) in the Municipality of Banikoara (Northern Benin)

Tode K. Michel [a,b*], Kawoun Alagbe Gildas [b,c], Tassigui Sabi Sio [c] and Ahamide Bernard [b]

[a] Doctoral School of Agronomic and Water Sciences (EDSAE), University of Abomey Calavi (UAC), Benin.
[b] Rural Engineering and Agricultural Machinery Laboratory (LGRMA), Faculty of Agronomic Sciences (FSA), University of Abomey Calavi, Benin.
[c] Pierre Pagney Laboratory: Climate, Water, Ecosystems and Development (LACEEDE), Faculty of Human and Social Sciences (FASHS), University of Abomey Calavi (UAC), Benin.

Authors' contributions

This work was carried out in collaboration among all authors. Author TKM designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors KAG and AB managed the field data collection and contributed to the literature review. Author TSS contributed to the climatic data analysis and reviewed the manuscript. All authors read and approved the final manuscript.

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**Corresponding author: E-mail: todemichel@yahoo.fr;*

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Abstract

Background: Seed cotton (*Gossypium hirsutum* L.) production in the municipality of Banikoara, in northern Benin, is severely constrained by climate variability and increasing rainfall deficits during critical stages of plant development.
Aims: This study aimed to evaluate the effects of deficit drip supplemental irrigation, calibrated to different fractions of the rainfall deficit relative to maximum evapotranspiration (ETM), on the phenological development and yield components of cotton over four consecutive cropping seasons.
Study Design: A randomised complete block design (RCBD) with five irrigation treatments and four replications was used.
Place and Duration of Study: The study was conducted at the cotton experimental perimeter in the municipality of Banikoara, Alibori Department, northern Benin, over four consecutive cropping seasons from June to November 2021 to 2024.
Methodology: Twenty elementary plots of 10 m² each were sown on 15 June at a density of 31,250 plants ha^{-1} (spacing of 0.80 m by 0.40 m). The five treatments corresponded to drip supplemental irrigation supplying 0% (T_0, strict rainfed control), 25% (T_{25}), 50% (T_{50}), 75% (T_{75}) and 100% (T_{100}) of the rainfall deficit relative to ETM, calculated according to the FAO 56 Penman-Monteith method. Phenological parameters and yield components were monitored fortnightly on 10 tagged plants per plot and analysed by two-factor ANOVA (Treatment by Year), with means separated by Duncan's Multiple Range Test at the 5% significance level.
Results: Supplemental irrigation significantly improved all phenological and agronomic parameters measured. Mean plant height at maturity rose from 60.65 cm (T_0) to 131.61 cm (T_{100}). Mean seed cotton yield increased from 750 kg ha^{-1} (T_0) to 3,725 kg ha^{-1} (T_{75}) and 3,700 kg ha^{-1} (T_{100}), representing gains of 397% and 393% relative to the rainfed control. Treatments T_{75} and T_{100} produced statistically equivalent yields, identifying 75% deficit compensation as the threshold for maximum water use efficiency and productivity.
Conclusion: These findings provide a robust empirical and technical framework for adapting cotton-growing practices to climate change in the Sudano-Sahelian zone, with 75% deficit compensation identified as the optimal water-saving strategy.

Keywords: Gossypium hirsutum L.; supplemental irrigation; deficit irrigation; drip irrigation; rainfall deficit; cotton phenology; seed cotton yield; evapotranspiration; water-saving strategy.

1. Introduction

Cotton (*Gossypium hirsutum* L.) is the principal cash crop and a strategic pillar of Benin's agricultural economy, contributing around 15 to 20% of national Gross Domestic Product (GDP) and more than 40% of export earnings (Ministry of Agriculture, Livestock and Fisheries [MAEP], 2023). The municipality of Banikoara, in the Alibori Department of northern Benin, represents the country's leading cotton-growing area. However, farming systems in this study area face considerable socio-economic and technical vulnerability under deteriorating hydroclimatic conditions (Soglo & Nonvide, 2019; Yégbémey *et al.*, 2013).

Simulations and projections from regional climate models (CORDEX Africa) over West Africa point to an intensification of the spatiotemporal variability of rainfall, marked by shifting rainy seasons and an increased recurrence of intraseasonal droughts (Gbobaniyi *et al.*, 2014; Traore *et al.*, 2014). This rainfall shift severely disrupts the traditional agricultural calendar and narrows the optimal sowing window for rainfed crops (Katé *et al.*, 2016; Traore *et al.*, 2014). Land-use change dynamics observed across Sudano-Sahelian Africa further reflect growing anthropogenic and environmental pressure on water and land resources (Zoungrana *et al.*, 2015).

Against this backdrop of water insecurity, deficit irrigation stands out as a major agronomic engineering strategy aimed at maximising crop water productivity (CWP) rather than absolute yield per unit area (Geerts & Raes, 2009; Zwart & Bastiaanssen, 2004). Applying drip micro-irrigation to cotton allows water to be delivered directly to the root system, reducing losses through direct soil evaporation and optimising the phenological response of plants under deficit stress (Yazar *et al.*, 2002). Where severe water stress during the vegetative or flowering phase reduces leaf area index, induces the abortion of reproductive organs and lowers mean boll weight, controlled supplemental irrigation helps preserve the photosynthetic apparatus and ensures optimal boll retention (Geerts & Raes, 2009; Yazar *et al.*, 2002). Recent cotton research indicates that carefully calibrated deficit irrigation can balance crop performance with irrigation water savings, with the appropriate level depending on the production environment and irrigation regime (Annu *et al.*, 2024; Liao *et al.*, 2025; Wang *et al.*, 2026). Comparable regulated-deficit approaches in other irrigated crops also support evaluating water applications as fractions of crop evapotranspiration when water availability is limited (Tufa *et al.*, 2024). For cotton specifically, a recent climate-oriented assessment further reinforces the importance of evaluating deficit irrigation strategies under local hydro-climatic conditions rather than assuming a uniform response across environments (Chen *et al.*, 2025).

Accordingly, the present study addresses the need to determine, under Banikoara conditions, how graded drip supplemental irrigation based on partial compensation of the rainfall deficit relative to ETM influences cotton phenology, boll retention and final yield across consecutive cropping seasons. The specific uncertainty examined is whether partial deficit compensation can provide phenological and yield responses comparable with full compensation.

This study aimed to evaluate, over four consecutive cropping seasons (2021 to 2024) in Banikoara, the effect of five drip supplemental irrigation compensation fractions (0%, 25%, 50%, 75% and 100% of the rainfall deficit relative to ETM) on the phenological behaviour, boll retention and final yield of cotton (*Gossypium hirsutum* L.).

2. Materials and Methods

2.1 Study Site

The experiment was conducted over four consecutive cropping seasons (June to November 2021, 2022, 2023 and 2024) in the municipality of Banikoara (11°17' to 11°41'N; 2°36' to 3°08'E), at the heart of the cotton-growing basin of northern Benin (Fig. 1).

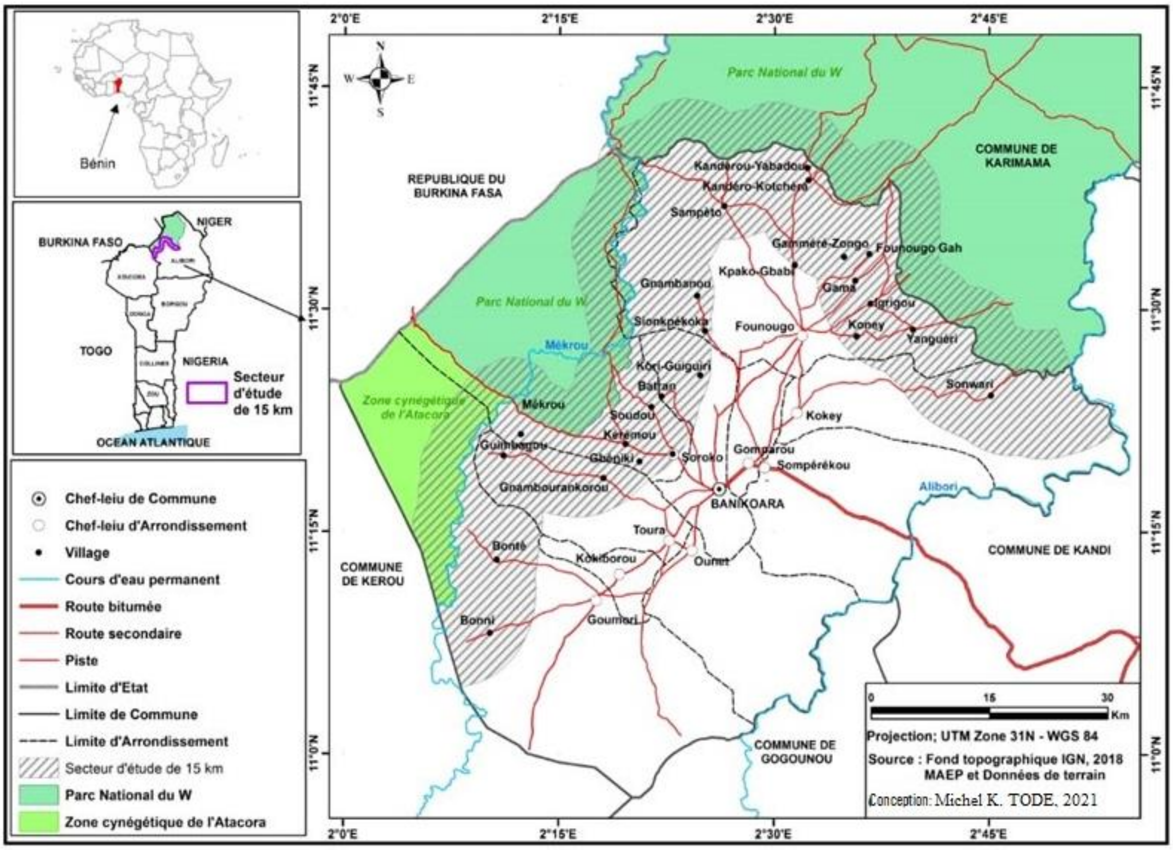

Fig. 1. Geographical and administrative location of the municipality of Banikoara

The climate is of the Sudano-Guinean type, with a single rainy season and mean annual rainfall of 900 to 1100 mm. The soil at the site is a ferruginous tropical leached Lixisol (FAO classification), with a sandy loam texture, a slightly acidic pH (6.2 to 6.8) and a low residual water-holding capacity.

2.2 Experimental Design and Treatments

A randomised complete block design (RCBD) comprising five treatments and four replications (20 elementary plots of 10 m² each) was established. Cotton was sown on the recommended date of 15 June (Katé *et al.*, 2016) at a planting density of 31,250 plants ha^{-1} (spacing of 0.80 m by 0.40 m). The five treatments evaluated corresponded to supplemental irrigation levels supplying calibrated fractions of the rainfall deficit as follows:

- **T_0:** 0% compensation (strict rainfed control);
- **T_{25}:** 25% compensation of the ETM deficit;
- **T_{50}:** 50% compensation of the ETM deficit;
- **T_{75}:** 75% compensation of the ETM deficit;
- **T_{100}:** 100% compensation of the ETM deficit.

2.3 Irrigation Scheduling and Water Requirement Calculation

Maximum crop evapotranspiration (ETM) was determined according to the standard FAO 56 Penman-Monteith protocol (Allen *et al.*, 1998):

$$ETM = ET_0 \times Kc$$

The weekly rainfall deficit (DP) and the irrigation dose were calculated as follows:

$$DP = ETM - P$$

$$\text{Irrigation dose (mm)} = DP \times (\text{irrigation fraction } \% / 100)$$

The crop coefficients (Kc) applied followed FAO 56 guidance (Allen *et al.*, 1998): 0.35 for the establishment and emergence phase; 0.60 to 1.15 during vegetative development; 1.15 to 1.20 during flowering and boll setting; and 0.70 to 0.50 during maturation. Irrigation was distributed through an integrated drip system (0.6 L h^{-1} per emitter, spaced 30 cm apart) at a rate of two to three applications per week during periods of deficit.

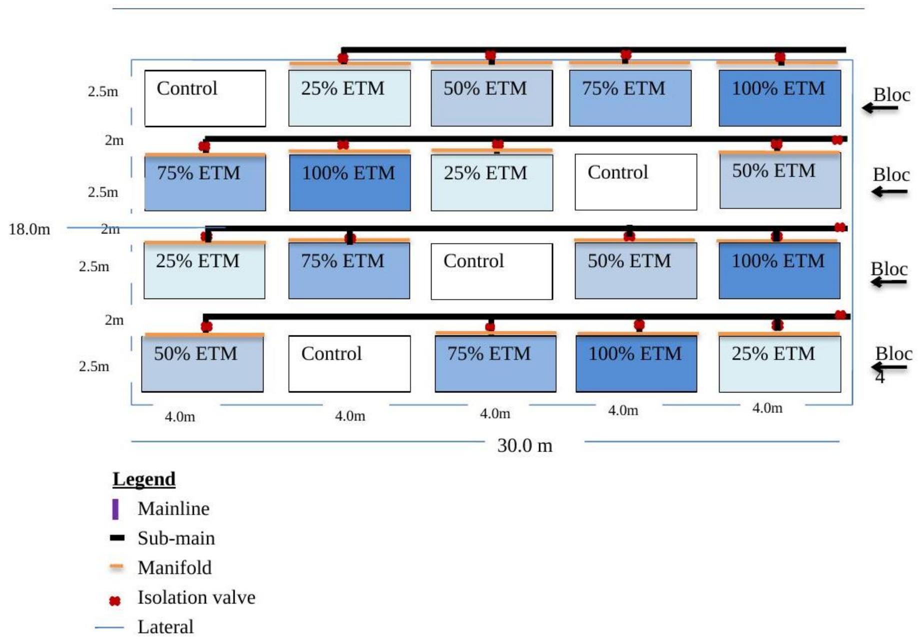

Fig. 2. Randomised complete block design of the cotton perimeter

2.4 Measurements and Statistical Analysis

Phenological parameters (plant height, number of monopodial and sympodial branches, floral density per m², boll formation and number of open bolls), together with yield components (gross and net seed cotton weight), were monitored fortnightly on a permanent sample of 10 plants per elementary plot. Data collected across the four cropping seasons were subjected to a two-factor analysis of variance (ANOVA) (Treatment by Year) using R software (v4.3.1). Means were separated using Duncan's Multiple Range Test (DMRT) at a significance threshold of $\alpha = 0.05$.

3. Results

3.1 Phenological Response to Supplemental Irrigation

3.1.1 Plant Height at Maturity

Supplemental irrigation exerted a highly significant effect on the vertical growth of cotton ($P < 0.001$). Mean height at maturity increased continuously with the level of irrigation, from 60.65 ± 0.02 cm under the rainfed treatment T_0 to 131.61 ± 2.60 cm under T_{100}. The difference between the 75% compensation treatment (125.99 cm) and the 100% treatment (131.61 cm) was not statistically significant ($P > 0.05$), indicating that a vegetative growth plateau was reached at and above 75% water supply. Comparable field evidence shows that cotton plant height is responsive to irrigation intensity, with milder deficit regimes supporting greater vegetative growth than more severe water restriction (Sampathkumar *et al.*, 2013).

3.1.2 Branching Dynamics

The total number of branches per plant at maturity differed significantly between treatments ($P < 0.001$), ranging from 12.0 ± 2.4 under T_0 to 17.8 ± 1.0 under T_{100} (Table 1). Treatments T_{75} and T_{100} were statistically homogeneous. Regular water supply stimulated the early appearance of fruiting branches (sympodia), accelerating the transition from the vegetative to the reproductive phase. Recent field evidence likewise indicates that irrigation strategy significantly influences monopodial and sympodial branch development in cotton, with improved water supply supporting greater branching (Kaur *et al.*, 2025).

3.1.3 Floral and Boll Dynamics

Floral production peaked during the twelfth week after sowing across all irrigation regimes. Maximum flower density ranged from 122.0 ± 2.9 flowers m^{-2} for the rainfed control T_0 to 158.5 ± 2.5 flowers m^{-2} for T_{100} and 148.5 ± 7.0 flowers m^{-2} for T_{75}. Boll formation followed the same trend: the maximum number of bolls formed per m^2 reached 97.5 under T_0, 130.0 under T_{75} and 132.5 under T_{100}. Maximum boll length ranged from 3.51 cm (T_0) to 5.26 cm (T_{75}) and 5.29 cm (T_{100}).

At harvest, the number of open bolls per m^2 stood at 74.2 under T_0, compared with 122.0 under T_{75} and 126.0 under T_{100}. The statistical similarity observed between T_{75} and T_{100} for boll-related parameters confirms the effectiveness of a water supply regulated at 75% of the ETM deficit. This response agrees with evidence that reduced irrigation from squaring to peak bloom can decrease the number of reproductive structures and green bolls, demonstrating the sensitivity of cotton reproductive development to water supply during this period (Herritt *et al.*, 2022).

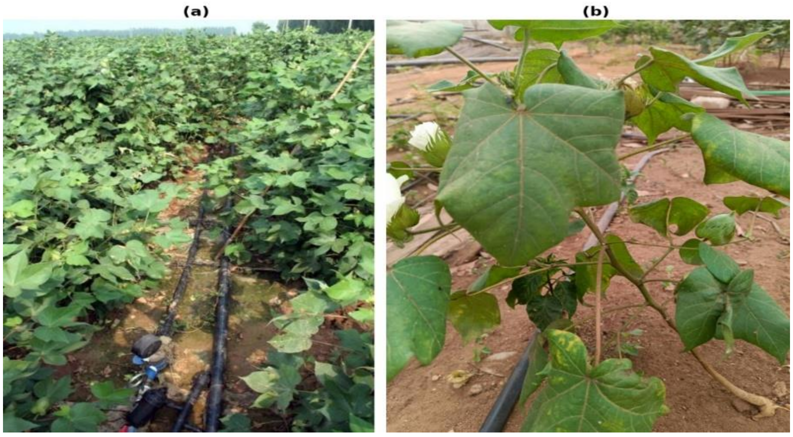

Plate 1. Overview of the in field drip network (a) and the phenological development showing open white flowers and young bolls in the process of filling (b)

This plate illustrates the key role of drip micro-irrigation in sustaining the reproductive dynamics of cotton (*Gossypium hirsutum L.*). It highlights the concurrence of full flowering and boll set, ensuring optimal retention of fruiting organs under water stress.

3.2 Yield Components and Seed Cotton Production

Supplemental irrigation had a very highly significant effect on seed cotton yield ($P < 0.001$) (Table 1). The mean net yield across the four years rose from 750 kg ha^{-1} under the non-irrigated control (T_0) to 1,900 kg ha^{-1} (T_{25}), 2,925 kg ha^{-1} (T_{50}), 3,725 kg ha^{-1} (T_{75}) and 3,700 kg ha^{-1} (T_{100}), corresponding, respectively, to yield gains of 153%, 290%, 397% and 393% relative to T_0. The absence of a statistical difference between T_{75} and T_{100} demonstrates the economic and agronomic relevance of the T_{75} treatment (Table 1). The yield response is consistent with a two-year drip-irrigation study in which a 75% irrigation level conserved water without significantly reducing seed cotton yield relative to full irrigation (Basal *et al.*, 2009).

Table 1. Annual net seed cotton yield (kg ha^{-1}) by treatment and year (2021 to 2024)

Treatment	2021	2022	2023	2024	Mean 2021 to 2024
T_0 (0%)	800	700	700	800	750 d
T_{25} (25%)	1,900	1,900	1,900	1,900	1,900 c
T_{50} (50%)	2,900	2,900	3,000	2,900	2,925 b
T_{75} (75%)	4,000	3,500	3,900	3,500	3,725 a
T_{100} (100%)	4,000	3,500	3,700	3,600	3,700 a

Means in the last column followed by different letters differ significantly at $P < 0.05$ (Duncan's test)

3.3 Interannual Variability

Two-factor analysis of variance revealed a significant year effect ($P < 0.05$), reflecting the impact of interannual rainfall variability on crop performance (Table 1). The years 2022 and 2023 recorded the lowest rainfed yield (700 kg ha^{-1} under T_0); in 2023, this corresponded to a particularly marked rainfall deficit sequence during flowering. However, the treatment-by-year interaction was not significant ($P > 0.05$), confirming the stability and repeatability of the irrigation treatment effects across the four cropping seasons.

Fig. 3 shows the interannual yield dynamics. Panel A presents the annual seed cotton yields for each treatment over the four seasons (2021 to 2024), allowing direct assessment of within-treatment interannual variability and cross-treatment comparisons within each year. Panel B presents the four-year means with their standard deviations and a trend line highlighting the yield response function to increasing irrigation fraction.

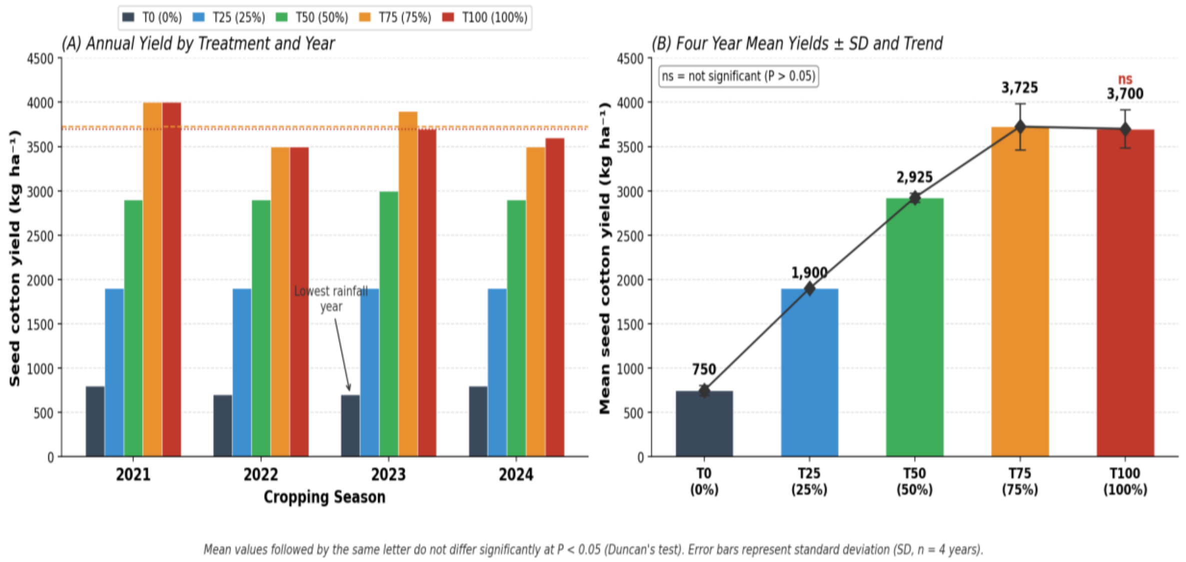

Fig. 3. Interannual variability in seed cotton yield under five drip supplemental irrigation treatments over the period 2021 to 2024. Panel A: annual yields (kg ha^{-1}) by treatment and season. Panel B: four year means ± standard deviation (SD) with an overlaid trend line

The dashed and dotted horizontal lines in Panel A indicate the four year means for T_{75} and T_{100} respectively. 'ns' denotes a non significant difference between T_{75} and T_{100} (P > 0.05, Duncan's test). Error bars in Panel B represent the standard deviation (SD, n = 4 years).
Source: data processing, June 2026

Two-factor ANOVA revealed a significant year effect ($P < 0.05$) on yield and most phenological parameters, reflecting interannual rainfall variability (Fig. 3A). The years 2021 and 2022 were characterised by relatively higher total rainfall and produced the greatest plant heights and boll numbers among the irrigated treatments. As shown in Fig. 3A, the year 2023 recorded a rainfed yield of 700 kg ha^{-1}, jointly the lowest value with 2022, consistent with the most severe rainfall deficit observed during that season and illustrating the acute vulnerability of cotton to uncompensated water stress.

Fig. 3B indicates a near-linear yield response to increasing irrigation fraction up to T_{75}, followed by a plateau between T_{75} and T_{100}. This water-yield response pattern, with a steep gain phase (T_0 to T_{75}: 397% increase) and a plateau phase (T_{75} to T_{100}: 0.7% decrease, not significant), is characteristic of regulated deficit irrigation in cotton (Geerts & Raes, 2009) and forms the quantitative basis for recommending T_{75} as the optimal irrigation strategy for Banikoara.

Critically, the treatment-by-year interaction was not significant ($P > 0.05$) for yield or for most phenological parameters. This statistical result confirms that the relative ranking and magnitude of treatment effects remained constant across all four seasons, regardless of interannual rainfall variability. As shown in Fig. 3A, the relative spacing between treatment bars remains remarkably stable from one year to the next, providing robust evidence that the conclusions of this study are not specific to a single year but hold across the full range of recent climate variability observed in Banikoara. Multi-year field evidence similarly shows that the magnitude of cotton yield and boll responses to irrigation varies with the occurrence and severity of seasonal moisture deficits, highlighting the importance of interannual climatic conditions (Pettigrew, 2004).

4. Discussion

4.1 Effect of Supplemental Irrigation on Phenology

The positive response of cotton growth and vegetative development to supplemental irrigation regimes corroborates well-established physiological mechanisms of water stress management. In the absence of sufficient water, stomatal closure reduces stomatal conductance and carbon fixation, restricting cell elongation and the development of the leaf canopy (Geerts & Raes, 2009; Yazar *et al.,* 2002). The limited height observed under the strict rainfed treatment T_0 (60.65 cm) illustrates the severe impact of water deficit on non-irrigated crops in northern Benin, consistent with the work of Zoungrana *et al.* (2015) on remote-sensing monitoring of vegetation dynamics in semi-arid West Africa.

Furthermore, the statistical equivalence observed between the T_{75} and T_{100} regimes validates the theoretical model of regulated deficit irrigation (RDI) developed by Geerts and Raes (2009) and experimentally verified by Yazar *et al.* (2002) in cotton. Partial compensation limited to 75% of the rainfall deficit was sufficient to maintain an adequate leaf water potential and to prevent the massive shedding of floral buds and young bolls.

Field experiments across four seasons have also shown that cotton growth characteristics respond to irrigation regime, while the wettest treatments may provide little additional yield benefit once adequate water supply is reached (DeTar, 2008).

4.2 Yield Response and Water Use Efficiency

The maximum yields achieved under supplemental irrigation (3,725 kg ha^{-1} under T_{75}) demonstrate the high agronomic potential of the crop once water stress is controlled. When analysing overall crop water productivity, these results align with the global review of Zwart and Bastiaanssen (2004), which shows that well-managed irrigation can achieve high crop water productivity while preserving yield. Treatment T_{75} saves 25% of the irrigation water volume required by T_{100} without inducing any loss of seed cotton yield, establishing it as the optimal water-efficiency strategy for the region. A global meta-analysis further showed that deficit irrigation can improve cotton water productivity while its effect on seed cotton yield depends strongly on irrigation amount, method, deficit timing, climate and soil conditions (Cheng *et al.*, 2021).

4.3 Implications for Climate Change Adaptation

Given the observed shift in agricultural calendars and the disruption of rainfall patterns across West Africa (Gbobaniyi *et al.,* 2014; Traore *et al.,* 2014), recourse to supplemental irrigation represents a decisive technical adaptation lever. Strict adherence to the 15 June sowing date (Katé *et al.,* 2016), combined with 75% deficit irrigation, helps secure cotton production against climatic uncertainty. Moreover, socio-economic surveys conducted in the cotton-growing zone of Benin show that producers are willing to change their farming practices when a technology offers a measurable response to climate variability (Soglo & Nonvide, 2019; Yégbémey *et al.,* 2013). Recent research in Benin further demonstrates that cotton performance under climate change is shaped by genotype × environment × management interactions, supporting the need for locally adapted production strategies (Aboua *et al.*, 2025).

5. Conclusion

Across four consecutive cropping seasons in Banikoara, supplemental drip irrigation consistently improved cotton phenological performance and seed cotton yield relative to rainfed production. Mean yield increased from 750 kg ha^{-1} under T_0 to 1,900, 2,925, 3,725 and 3,700 kg ha^{-1} under T_{25}, T_{50}, T_{75} and T_{100}, respectively. The absence of a significant difference between T_{75} and T_{100} indicates that compensating 75% of the rainfall deficit relative to ETM was sufficient to attain the yield plateau observed under the experimental conditions. This treatment also required 25% less irrigation water than full deficit compensation while maintaining statistically equivalent yield. The stability of treatment effects across the four seasons further indicates that the response was repeatable under the interannual rainfall variability observed during the study. On the basis of the measured phenological and yield responses, T_{75} represents the most favourable irrigation level evaluated for balancing seed cotton production with reduced supplemental water application in Banikoara. These findings support the use of calibrated supplemental irrigation where rainfall deficits constrain cotton production, while remaining specific to the conditions evaluated in this experiment.

6. Limitations

This study was conducted at a single experimental site in Banikoara over four cropping seasons, using 20 plots and 10 monitored plants per plot. The evaluation was restricted to five fixed irrigation-compensation levels and the prevailing soil and climatic conditions of the study area. Although interannual rainfall variability was considered, the findings may not fully represent cotton responses under other environments, soil types, or rainfall regimes. Future studies should include multiple locations, longer-term evaluations, and broader irrigation regimes to confirm the generalisability of the observed responses.

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Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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