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Biostimulant Benefits Under Deficit Irrigation Do Not Ensure Water Saving Compensation: A Dual Benchmark Analysis of Reproductive Sink Limitation in Cotton

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Abstract

Biostimulants may improve crop performance under deficit irrigation, but whether such benefits are sufficient to compensate for reduced irrigation input remains unclear. We evaluated poly-γ-glutamic acid, potassium humate, brown algal oligosaccharides, and plant polyphenols in drip irrigated cotton under nominal seasonal irrigation quotas of 4500 and 3600 m^3 ha^{-1}. Treatment performance was evaluated using a dual benchmark framework: against the untreated control under reduced irrigation and against the corresponding treatment under higher irrigation. Although three biostimulants increased measured seed cotton yield by 10.7–17.3% relative to the reduced irrigation control, cross regime yield retention reached only 64.9–69.9%, while plant polyphenols retained 46.4%. All treatments remained below the 80% production retention threshold required to maintain nominal irrigation water productivity after a 20% reduction in irrigation input. Yield component decomposition localized the compensation shortfall primarily to reproductive sink number: boll number retention ranged from 52.9% to 70.5%, whereas single boll mass retention remained substantially higher at 87.6–108.1%. Maintenance or enhancement of boll mass therefore buffered yield loss but could not offset the reduction in harvestable boll number. Terminal biomass retention ranged from 65.9% to 150.8% but did not track yield retention, indicating that late season growth recovery was decoupled from reproductive recovery. These results reveal a clear distinction between biostimulant efficacy under deficit irrigation and actual compensation for reduced water input. Dual benchmarking links water savings directly to production retention, providing a stronger basis for evaluating irrigation reduction strategies and identifying reproductive sink preservation as the key biological target for improving compensation in cotton.

Keywords: deficit irrigation; cotton; biostimulant; boll retention; irrigation water productivity; source sink relations; yield compensation

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1. Introduction

Water scarcity increasingly constrains agricultural production in arid and semi-arid regions, where irrigation management must reduce water inputs without compromising crop productivity. Crop responses to water limitation vary with stress intensity, developmental stage, genotype, soil conditions, and management context [1]. In cotton, deficit irrigation often improves water productivity while reducing seed cotton yield. A global meta-analysis

showed that deficit irrigation increased cotton water productivity on average but caused a concurrent decline in yield, with substantial variation among irrigation strategies and environmental conditions [2]. More recent syntheses have likewise demonstrated strong environment and management dependent variation in cotton water and nitrogen use efficiencies [3]. The central challenge is therefore not simply to reduce irrigation, but to retain sufficient crop production for the water saved.

Yield loss under reduced irrigation is not necessarily proportional to the decrease in water supply. Complementary management can partly offset production penalties by improving crop resource use and irrigation efficiency. Field studies show that coordinated irrigation and nitrogen management, together with appropriate irrigation scheduling, can improve yield retention and water productivity under limited water supply [4–6]. More broadly, water saving interventions should be evaluated by considering both the amount of irrigation withdrawn and the crop production retained [7].

Plant biostimulants are increasingly proposed as complementary tools for sustaining crop performance under water limitations. Broad syntheses report positive average responses but also emphasize strong dependence on crop species, environment, formulation, dose, and application strategy [8,9]. Humic substances can influence root development, nutrient acquisition, membrane activity, and stress responses, with effects that depend on source and molecular composition [10]. Seaweed derived products contain heterogeneous polysaccharides, oligosaccharides, minerals, and signaling active compounds and therefore cannot be assumed to share a uniform mode of action [11]. Poly-γ-glutamic acid can modify drought-related physiological responses and has shown cotton specific effects on stress regulation [12,13]. These mechanisms support the use of biostimulants under deficit irrigation, but improved performance under water limitations does not necessarily mean that the production loss associated with irrigation reduction has been compensated.

This distinction creates an important benchmarking problem. Biostimulant efficacy is commonly evaluated by comparing a treated crop with an untreated crop exposed to the same reduced irrigation regime. Such a comparison identifies within-regime efficacy, namely whether the treatment improves crop performance under a given level of water limitation. It does not determine cross-regime compensation, that is, whether the same treatment retains sufficient production when irrigation is reduced from a higher water baseline. A treatment may therefore outperform the reduced irrigation control while still producing substantially less than the corresponding treatment under higher irrigation. These two comparisons answer different agronomic questions: the first identifies a treatment benefit under stress, whereas the second determines whether that benefit is sufficient to compensate for the production loss associated with irrigation reduction.

The distinction becomes especially important when irrigation water productivity is used to evaluate water saving strategies. If irrigation input is reduced by a known fraction, production must be retained by at least the same fraction to maintain irrigation water productivity. The relevant question is therefore not only whether a biostimulant increases crop production under reduced irrigation but whether the retained production is sufficient relative to the water saved. A dual benchmark approach can address these questions simultaneously by comparing treatment performance both with the untreated crop under reduced irrigation and with the corresponding treatment under higher irrigation. This framework directly links treatment response to the resource saving objective of irrigation management and separates stress regime improvement from successful compensation for reduced water input.

Beyond determining whether compensation occurs, it is also necessary to identify where the compensation gap arises within the yield formation process. Cotton yield integrates the establishment, persistence, and filling of reproductive sinks. Water limitation

can reduce fruit initiation and boll retention, particularly when stress occurs during sensitive reproductive stages [14,15]. The number of harvestable bolls is strongly influenced by the establishment and persistence of reproductive structures, including boll loss and abscission under water deficit [16,17]. By contrast, the mass of surviving bolls may be maintained or increased when assimilate availability per retained sink is comparatively less constrained [18,19]. Yield loss can therefore arise primarily from reduced reproductive sink numbers even when filling of the surviving bolls remains relatively stable.

The timing of crop recovery adds a second mechanistic dimension. Water limitation during flowering and early boll development may reduce reproductive sink number before later biomass accumulation occurs. Once reproductive opportunities have been lost, subsequent vegetative growth or increased growth of the remaining sinks may not fully restore final yield. Cotton reproductive development is particularly sensitive to the timing of water deficit, and stress during flowering and boll setting can have lasting effects on fruit retention [14,15]. Dry matter production and partitioning further indicate that reproductive timing and crop maturity strongly influence the conversion of accumulated biomass into harvestable cotton [19,20]. Consequently, similar late-season biomass does not necessarily imply similar yield if crops retained different numbers of reproductive sinks earlier in development.

Yield component decomposition provides a direct means of diagnosing this compensation gap. At a common stand density, boll number per plant and single boll mass jointly describe the reproductive components underlying measured seed cotton yield; the reported yield itself was obtained from plot harvest weights. A decline in boll number can therefore only be offset when boll mass increases sufficiently to compensate for that loss. Separating these components distinguishes inadequate reproductive sink retention from inadequate filling of the sinks that remain. Comparison with stage specific biomass further indicates whether later growth recovery coincides with, or occurs after, the developmental window that determines final boll number. Together, these analyses connect the resource accounting question of irrigation compensation with the crop development processes underlying production retention.

In this study, we evaluated poly-γ-glutamic acid (PGA), potassium humate (KH), brown algal oligosaccharides (BAO), and plant polyphenols (PP) in drip irrigated cotton under nominal seasonal irrigation quotas of 4500 and 3600 m^3 ha^{-1}. We developed a dual benchmark framework to determine whether treatment benefits under reduced irrigation translated into sufficient production retention after irrigation input was reduced. Specifically, we quantified (i) treatment responses relative to the untreated crop under reduced irrigation, (ii) matched measured seed cotton yield and irrigation water productivity retention across irrigation regimes, (iii) the gap between observed production and that required to maintain irrigation water productivity, (iv) the relative contributions of boll number and single boll mass to yield retention, and (v) stage specific biomass recovery. We hypothesized that positive treatment responses within the reduced irrigation regime could coexist with incomplete cross regime compensation, that loss of boll number would represent the principal constraint on production retention, and that late biomass recovery would not compensate for yield loss once reproductive sink number had been reduced.

2. Materials and Methods

2.1. Experimental Site and Crop Management

The field experiment was conducted under mulched drip irrigation at the Agricultural Experimental Station of Shihezi University, Xinjiang, China (86°03′45″ E, 44°18′29″ N). The experimental site represents a typical arid cotton production environment in which irrigation is a major determinant of crop growth and productivity. The experiment was

conducted in an arid continental climate in the Shihezi region of Xinjiang, China. Previous studies at Shihezi University experimental fields reported alkaline soils (pH 7.9–8.1) and soil organic matter contents of 14.9–25.6 g kg^{-1}.

2.2. Experimental Design and Irrigation Treatments

A two level irrigation experiment was used to evaluate whether biostimulant application could compensate for reduced irrigation input. The higher irrigation regime (W1) received a nominal seasonal irrigation quota of 4500 m^3 ha^{-1}, whereas the reduced irrigation regime (W2) received 3600 m^3 ha^{-1}, representing a 20% reduction in irrigation input. The experiment comprised 19 treatments (T0–T18) across two irrigation regimes. Under W2, T0 was the untreated control; T1–T4 received PGA, KH, BAO and PP individually; T5–T7 received PP + PGA, PP + BAO and PP + KH, respectively; and T8–T10 received the same three combinations at 1.5 times their component doses. Under W1, T11 was the untreated control; T12–T13 received PP + PGA and PP + BAO; T14–T17 received PGA, KH, BAO and PP individually; and T18 received PP + KH. The four matched single-product pairs (T14/T1, T15/T2, T16/T3 and T17/T4) formed the prespecified comparison set for cross regime compensation (Table 1). Both irrigation regimes included untreated controls, and the complete code and dose key is reported in Table S8. The three elevated-dose combinations were tested only under W2 and therefore were not included in the matched cross-regime analysis. The biostimulants were diluted with local irrigation water and applied through the drip irrigation system in three equal applications, approximately on 5 June, 25 June and 15 July 2025, at the squaring, early flowering and flowering boll development stages, respectively. Each application was associated with 100 m^3 ha^{-1} of irrigation water. Seasonal application rates were 15 kg ha-1 PGA, 10 kg ha-1 KH, 0.5 kg ha-1 BAO and 0.3 kg ha^{-1} PP. Combination treatments used the sum of the component doses; for 1.5-fold treatments, each component dose was multiplied by 1.5. The W2 irrigation regime was implemented from the beginning of the experimental irrigation treatment, with a seasonal quota of 3600 m^3 ha^{-1} compared with 4500 m^3 ha^{-1} under W1. Poly-γ-glutamic acid (PGA), potassium humate (KH), brown algal oligosaccharides (BAO), and plant polyphenols (PP) were purchased from Shanghai Aladdin Biochemical Technology Co., Ltd. (Shanghai, China).

Table 1. Treatment structure used for the primary matched cross-regime comparison.

Treatment	W1 4500 m^3 ha^{-1}	W2 3600 m^3 ha^{-1}
Untreated control	—	T0
PGA	T14	T1
KH	T15	T2
BAO	T16	T3
PP	T17	T4

Note: Treatment reference definitions: T0 was the untreated control under W2 and T11 was the untreated control under W1. T18 was the W1 PP + KH combination, not an untreated control. Within-regime treatment responses were referenced to T0 or T11 as appropriate; comparisons involving T18 were active treatment contrasts only.

Plant polyphenols (PP) were selected as the common component in the combined biostimulant treatments based on their potential role in antioxidant defense and stress regulation. Water limitation affects multiple physiological processes in plants, including cellular redox homeostasis, osmotic adjustment, and nutrient acquisition. Compared with PP, PGA has been associated with soil water retention and osmotic adjustment, BAO with the regulation of stress-responsive signaling pathways, and KH with root development and nutrient acquisition. These distinct but potentially complementary functions provided the rationale for combining PP with each of the other three biostimulants. Furthermore,

maintaining PP as a common component allowed systematic comparisons among different combination formulations and application rates. This experimental design was intended to evaluate whether combining biostimulants with different functional characteristics could improve cotton productivity under deficit irrigation.

2.3. Plant Growth, Biomass, Leaf Area, and SPAD Measurements

Plant measurements were available at the squaring, flowering boll setting, and boll opening stages. Recorded organ dry masses were corrected for the 2.41 g container tare where applicable. Total plant dry mass was calculated as the sum of root, stem, leaf, and reproductive organ dry masses (Table S2):

$$DM_{total} = DM_{root} + DM_{stem} + DM_{leaf} + DM_{reproductive} \quad (1)$$

The reproductive biomass fraction was calculated as:

$$RF(\%) = \frac{DM_{reproductive}}{DM_{total}} \times 100\% \quad (2)$$

Leaf area was estimated from leaf length, leaf width, leaf number, and a shape coefficient of 0.75:

$$LA = L \times W \times N \times 0.75 \quad (3)$$

where L and W are leaf length and width, respectively, and N is leaf number.

SPAD values were used as chlorophyll meter readings. Missing observations were retained as missing values and were not imputed. (Table S3; Figure S2).

Samples of each organ of the plants were dried in an electrically heated forced-air drying oven (DHG-9240A, Shanghai Yiheng Scientific Instrument Co., Ltd., Shanghai, China), and the dry weight was measured using an electronic analytical balance (ME204E, METTLER TOLEDO, Greifensee, Switzerland). The length and width of the leaves were measured with a ruler, and the SPAD value of the leaves was determined using a portable chlorophyll meter (SPAD-502Plus, Konica Minolta, Osaka, Japan).

2.4. Measured Seed Cotton Yield and Irrigation Water Productivity

Seed cotton was harvested and weighed separately from each independent experimental plot. Harvested seed cotton mass was converted to a hectare-area basis (kg ha^{-1}) using the corresponding harvested plot area. Each treatment comprised three independent plots ($n = 3$); treatment-level measured seed cotton yield is reported as mean ± sample standard deviation (SD). Boll number per plant and single-boll mass were evaluated separately as yield-component traits and were not used to estimate the reported harvested yield.

$$Y = (\text{harvested seed cotton mass/harvested plot area}) \times 10{,}000 \quad (4)$$

Plot level irrigation water productivity (*IWP*, kg m^{-3}) was calculated as plot level measured seed cotton yield (kg ha^{-1}) divided by the corresponding seasonal irrigation input (m^3 ha^{-1}): 4500 for W1 and 3600 for W2.

$$IWP = \frac{Y}{IW} \quad (5)$$

IWP represents productivity per unit of applied irrigation water, not evapotranspiration-based water use efficiency. Treatment-level *IWP* is summarized across the three independent plots as mean ± SD.

The independent experimental unit was the field plot (three plots per treatment). The four primary matched single-biostimulant pairs (with three additional standard-dose matched PP-based mixtures) were PGA (T14/T1), KH (T15/T2), BAO (T16/T3), and PP

(T17/T4), with W1/W2 denoting 4500/3600 m^3 ha^{-1}. The field plot was the independent experimental unit (n = 3 plots per treatment). Treatment summaries are reported as means ± SD where plot-level variability is available. Within-irrigation comparisons use the respective untreated control, whereas cross irrigation comparisons use dose matched formulations. Percentage changes, yield retention and compensation gaps are descriptive transformations of treatment means.

2.5. Dual Benchmark Evaluation Framework

Treatment performance was evaluated using two complementary benchmarks. The framework links the matched W1–W2 treatment structure to three sequential questions: (i) whether a product improves measured yield within W2 relative to the untreated W2 control, (ii) whether the same product retains sufficient production after irrigation is reduced, and (iii) whether retained production reaches the 80% arithmetic boundary required to maintain nominal IWP. The first benchmark quantified relative benefit (RB) within the reduced irrigation regime:

$$RB(\%) = \left(\frac{Y_{W2,\ treatment}}{Y_{W2,\ control}} - 1\right) \times 100\% \quad (6)$$

This metric quantifies within regime efficacy, i.e., the extent to which a treatment improved measured yield relative to the untreated crop receiving the same reduced irrigation input.

The second benchmark quantified cross regime production retention for each matched treatment:

$$RR(\%) = \frac{Y_{W2,\ treatment}}{Y_{W1,\ treatment}} \times 100\% \quad (7)$$

where *PR* is production retention following irrigation reduction.

$$\frac{IW_{W2}}{IW_{W1}} = 0.8 \quad (8)$$

Maintenance of W1 irrigation water productivity requires:

$$\frac{Y_{W2}}{Y_{W1}} \geq \frac{IW_{W2}}{IW_{W1}} = 0.8 \quad (9)$$

Thus, *PR*% was defined as the production retention threshold required to maintain or improve nominal *IWP* after the 20% reduction in irrigation input (Table S7).

2.6. Yield Component and Biomass Retention Analysis

To examine the component basis of cross-regime production retention, we compared the W2/W1 ratios of boll number per plant and single-boll mass alongside independently measured plot-harvest yield. The product of the two component ratios was used as a descriptive approximation of yield retention, not as the method used to calculate harvested seed cotton yield. Retention ratios were also calculated for stage-specific total biomass:

$$R_{BN}(\%) = \frac{BN_{W2}}{BN_{W1}} \times 100\% \quad (10)$$

$$R_{BM}(\%) = \frac{BM_{W2}}{BM_{W1}} \times 100\% \quad (11)$$

$$R_{Bio}(\%) = \frac{Bio_{W2}}{Bio_{W1}} \times 100\% \quad (12)$$

where *RBN*, *RBM*, and *RBio* represent retention of boll number, single boll mass, and stage specific total biomass, respectively. These metrics were used to distinguish loss of reproductive sink number from changes in sink size and to evaluate whether biomass recovery across crop development was accompanied by corresponding production recovery.

2.7. Soil Chemical Properties and Soil Water

Soil chemical measurements were available for the 0–20 and 20–40 cm soil layers at three crop development stages. Measured variables included soil pH, organic matter, nitrate N, ammonium N, available P, available K, and electrical conductivity. These variables were analyzed as residual soil properties (Table S4). Soil water observations were available from three sampling rounds and nine depth intervals extending to 100 cm (Figure S1). Soil samples were collected from the 0–20 and 20–40 cm soil layers at three cotton growth stages. Soil pH and electrical conductivity (EC) were measured using a pH meter (FE28-Standard, METTLER TOLEDO, Greifensee, Switzerland) and a conductivity meter (DDS-307S, Shanghai INESA Scientific Instrument Co., Ltd., Shanghai, China), respectively. Soil organic matter was determined using the potassium dichromate oxidation method. Soil nitrate nitrogen (NO_3^--N) and ammonium nitrogen (NH_4^+-N) were extracted with potassium chloride solution and quantified using a continuous flow analyzer (SAN++, Skalar Analytical B.V., Breda, the Netherlands). Soil available phosphorus was determined using sodium bicarbonate extraction followed by molybdenum–antimony colorimetry, while available potassium was measured by flame photometry after ammonium acetate extraction. Soil samples for moisture determination were collected from different depth intervals within the 0–100 cm soil profile at three sampling times, and gravimetric soil water content was determined using the oven-drying method.

2.8. Data Screening and Analytical Dataset

All 19 treatment identities were verified against the study-team-confirmed allocation (Table S8). Plot-harvest seed cotton yield was measured independently, and the field plot was the experimental unit (three independent plots per treatment). The primary matched cross-regime comparisons involved the four single-product pairs: PGA T14/T1, KH T15/T2, BAO T16/T3 and PP T17/T4 (W1/W2). Within-regime untreated-control contrasts used T11 under W1 and T0 under W2. The three standard-dose PP combinations were represented under both irrigation regimes (T12/T5, T13/T6 and T18/T7), whereas the elevated-dose combinations T8–T10 were represented only under W2. Combination comparisons were treated as secondary descriptive analyses and were not pooled into the four-product primary compensation estimates.

2.9. Compensation Gap and Yield Component Decomposition

For each matched treatment, the W2 yield required to maintain W1 irrigation water productivity was calculated as:

$$Y_{W2,required} = 0.8 \times Y_{W1} \quad (13)$$

The compensation gap was then calculated as:

$$Gap = Y_{W2,required} - Y_{W2,observed} \quad (14)$$

A positive value indicated that observed production under W2 remained below the level required to maintain W1 *IWP*. The additional production required to close this gap was also expressed relative to observed W2 yield:

$$Gap_{relative}(\%) = \frac{Gap}{Y_{W2,observed}} \times 100\% \quad (15)$$

The cross regime production loss was additionally expressed per unit of irrigation saved:

$$P_{water} = \frac{Y_{W1} - Y_{W2}}{IW_{W1} - IW_{W2}} \quad (16)$$

where $IWW1 - IWW2 = 900$ m^3 ha^{-1}. This metric represents the estimated production loss associated with each cubic meter of irrigation withheld over the observed irrigation contrast.

For descriptive interpretation, the product of boll-number and single-boll-mass ratios was compared with independently measured yield retention. Logarithmic changes in the two components were then used to summarize their relative contributions to this component-based approximation, rather than to establish an exact identity for measured plot-harvest yield:

$$ln\left(\frac{Y_{W2}}{Y_{W1}}\right) = ln\left(\frac{BN_{W2}}{BN_{W1}}\right) + ln\left(\frac{BM_{W2}}{BM_{W1}}\right) \quad (17)$$

Small differences between component-product retention and independently measured yield retention are expected; the component-based calculation is an approximation and may also reflect sampling and stand-density differences. Component contributions were expressed relative to the sum of the two component logarithmic changes. A negative contribution indicates partial buffering by increased boll mass, whereas a positive contribution indicates an additional component decline. Treatment rankings were compared across four decision criteria: within W2 relative benefit, matched yield retention, W2 irrigation water productivity, and change in IWP between W1 and W2.

2.10. Statistical and Descriptive Analyses

The independent field plot was the experimental unit (three plots per treatment). Reported yields and growth variables are treatment means, with SD representing variation among independent plots where available. For the seven dose-matched W1/W2 formulation pairs, exploratory two-sided Welch tests were calculated from treatment means, reported SDs and $n = 3$ plots per group, with Holm adjustment across seven comparisons. Statistical analyses were performed using Python (version 3.11.9; Python Software Foundation, Wilmington, DE, USA). Exploratory two-sided Welch's *t*-tests were conducted for the specified treatment comparisons, with Holm adjustment applied to account for multiple comparisons.

3. Results

3.1. Dual Benchmarking Separated Within Regime Efficacy from Irrigation Compensation

The dual benchmark framework separated three sequential questions of treatment performance (Figure 1). First, the within regime benchmark compared each biostimulant treated crop with the untreated control under W2, thereby quantifying treatment efficacy within the same reduced irrigation environment [21]. Second, the matched cross regime benchmark compared each W2 treatment with the same treatment under W1 and therefore quantified the fraction of higher irrigation production retained after irrigation was reduced. Third, because W2 supplied 3600 m^3 ha^{-1} compared with 4500 m^3 ha^{-1} under W1, the irrigation ratio was 0.80; maintenance of nominal irrigation water productivity therefore required at least 80% production retention. These criteria distinguish improvement of the stressed state from retention of the higher water production level and from attainment of the water productivity break even boundary [22–24]. This framework allows a positive response relative to the W2 control to coexist with failed irrigation compensation. The treatment level results were therefore interpreted first against the within W2 control and then against the matched W1 treatment and the 80% retention boundary.

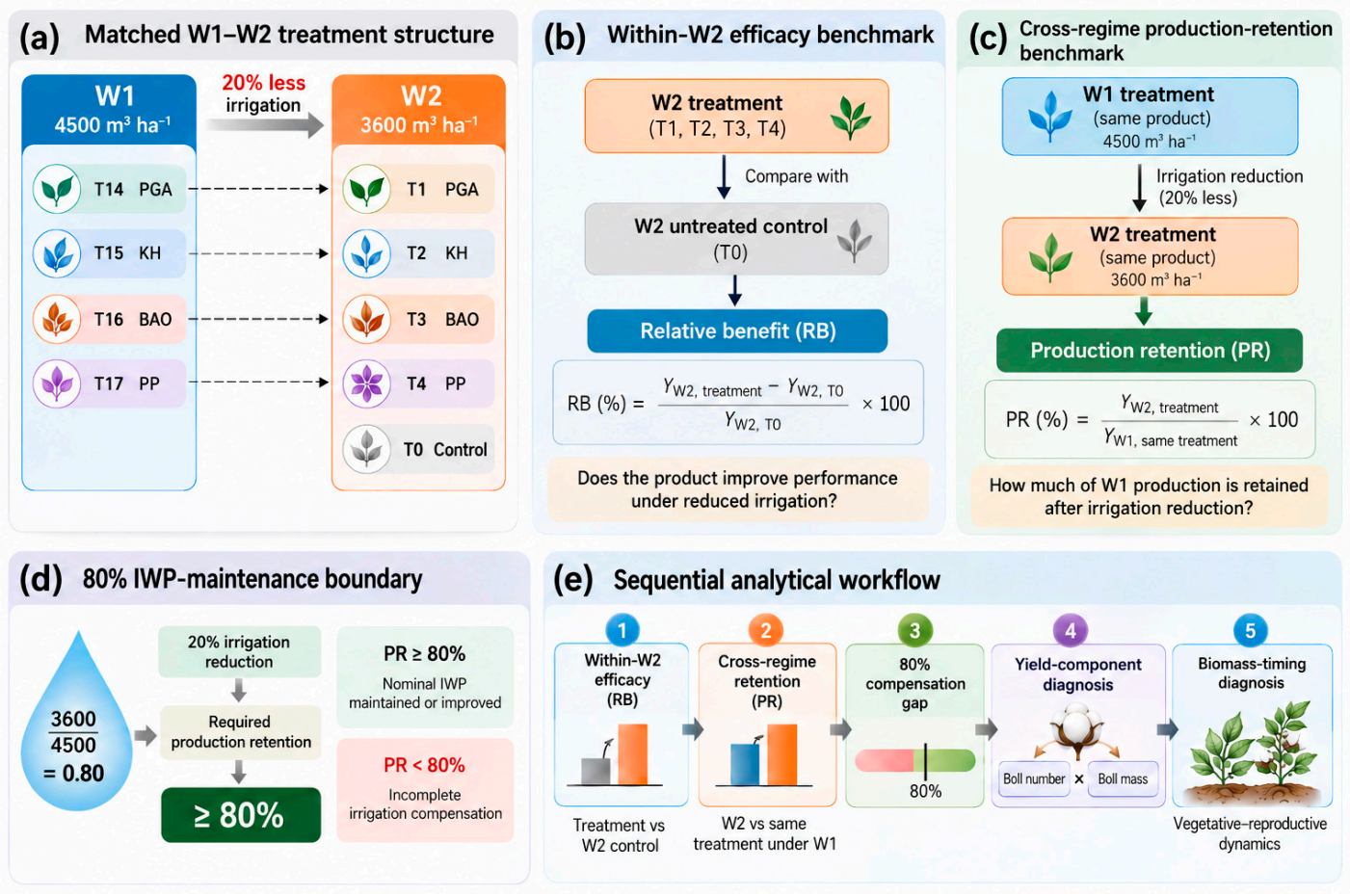

Figure 1. Dual benchmark framework for distinguishing within-regime efficacy from cross-regime irrigation compensation. (**a**) Matched W1 and W2 treatment structure for PGA, KH, BAO, and PP, with the untreated W2 control shown separately. (**b**) Within regime efficacy benchmark, comparing each W2 treatment with the untreated W2 control. (**c**) Cross-regime production retention benchmark comparing each W2 treatment with its matched W1 treatment. (**d**) Derivation of the 80% production retention boundary from the 3600/4500 irrigation ratio. (**e**) Sequential analytical logic from within W2 response to compensation gap, yield component diagnosis, and biomass timing.

Evaluation against the untreated W2 control indicated positive within regime responses for three of the four biostimulants. PGA, KH, and BAO increased measured seed cotton yield by 17.3%, 10.7%, and 13.7%, respectively, whereas PP reduced measured yield by 18.6% relative to the W2 control. PGA therefore showed the largest yield benefit when treatment performance was evaluated solely within the reduced irrigation regime (Figure 2a,b; Table 2). Matched W1–W2 comparisons produced a substantially different assessment. Cross regime yield retention was 66.8% for PGA, 64.9% for KH, 69.9% for BAO, and 46.4% for PP. Because all four values remained below the 80% boundary defined in Figure 1, none of the treatments maintained nominal W1 irrigation water productivity after the 20% reduction in irrigation input. Their distances below this boundary were 13.2, 15.1, 10.1, and 33.6 percentage points, respectively. Correspondingly, IWP declined by 16.5% for PGA, 18.9% for KH, 12.6% for BAO, and 42.0% for PP (Figure 2c–e; Table 2). This pattern is consistent with the broader cotton literature showing that deficit irrigation can improve or maintain water productivity while simultaneously reducing crop production, and that the magnitude of this trade off depends strongly on irrigation amount, timing, and production environment [25–27]. The dual benchmark response space in Figure 2d provides a compact visual separation between stress regime efficacy and cross regime compensation: PGA occupies the highest within W2 response position, whereas BAO is closest to the 80% retention boundary. This two axis

representation makes the benchmark dependent rank change visible without relying on a single treatment ranking. Across seven dose-matched formulations, W2/W1 yield retention ranged from 46.4% to 69.9%, below the 80% nominal IWP-maintenance benchmark for every formulation (Figure S4).

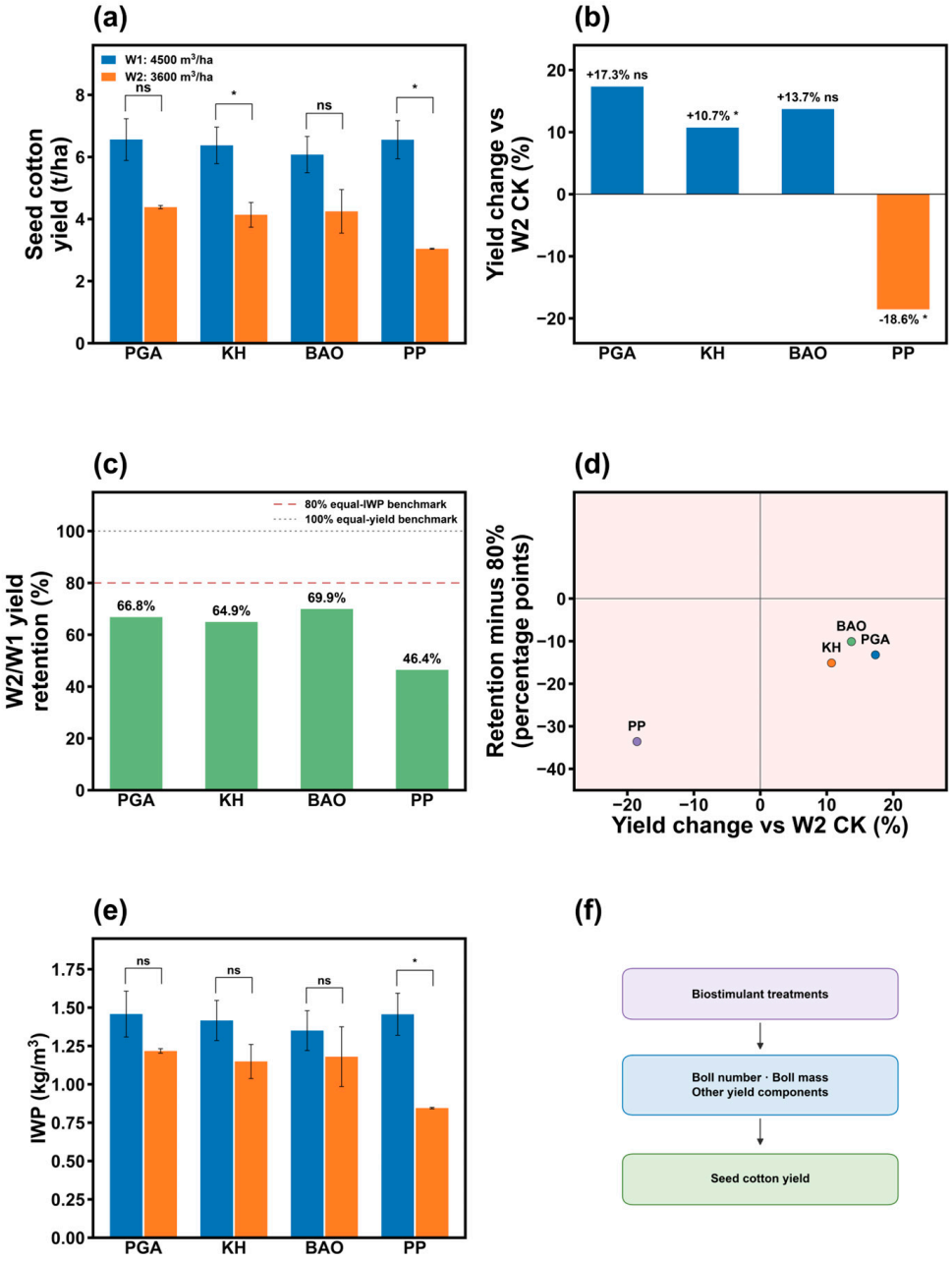

Figure 2. Benchmark-dependent production and irrigation water productivity responses. (**a**) Paired W1 and W2 measured seed cotton yield for PGA, KH, BAO, and PP; (**b**) within-W2 yield response relative to the untreated W2 control; (**c**) cross-regime yield retention relative to the 80% nominal IWP-maintenance boundary; (**d**) dual-benchmark response space; (**e**) irrigation water productivity (IWP) under W1 and W2; (**f**) conceptual illustration of the roles of boll number and single-boll mass in yield formation. Error bars represent standard deviations ($n = 3$ independent plots per treatment). Statistical comparisons were performed using two-sided Welch's *t*-tests based on group summary statistics, with Holm correction across seven dose-matched formulations for cross-regime comparisons and ten biostimulant treatments for within-W2 comparisons. ns, not significant; * $p < 0.05$. Panels (**c**,**d**) represent descriptive transformations of treatment means.

Table 2. Dual-benchmark performance, statistical comparisons, and yield-component retention of four dose-matched single-product treatments.

Treatment	Within W2 Response (%)	Yield Retention (%)	Gap (pp)	IWP Change (%)	BN Retention (%)	BM Retention (%)	Within W2 P	W1 vs. W2 P
PGA	17.3	66.8	−13.2	−16.5	70.5	94.7	0.004	0.054
KH	10.7	64.9	−15.1	−18.9	64.7	101.0	0.959	0.039
BAO	13.7	69.9	−10.1	−12.6	64.7	108.1	0.970	0.054
PP	−18.6	46.4	−33.6	−42.0	52.9	87.6	0.022	0.040

Note: Relative response indicators were calculated from treatment means. p values were obtained using two-sided Welch's t-tests based on treatment means, standard deviations, and independent experimental replication ($n = 3$), with Holm correction for multiple comparisons.

Seven dose-matched W1/W2 formulation comparisons are shown in Figure S4. Error bars represent SD across three independent field plots per treatment; Figure S4 identifies exploratory Holm-adjusted Welch p values calculated from reported group summary statistics. Seed cotton yield was measured independently from plot harvests, and IWP was calculated as measured yield divided by seasonal irrigation input. The yield-retention percentages and compensation gaps are descriptive transformations of treatment means. The treatment ranking also changed with the evaluation benchmark. PGA ranked first for improvement relative to the W2 control, whereas BAO ranked first for cross regime yield retention and showed the smallest IWP decline. Thus, the treatment producing the largest advantage over the stressed control was not the treatment that best preserved its corresponding higher irrigation production. This distinction is important because previous cotton studies have shown that management practices can increase yield or water productivity under restricted irrigation without producing equivalent responses in all components of crop performance (Table 2) [3,26,28]. Panel (f) provides a conceptual illustration of how boll number and single-boll mass contribute to yield formation; it is not the calculation method for the measured plot-harvest seed cotton yield. Table 2 instead summarizes the observed retention of yield components alongside the measured yield response.

The absolute magnitude of the cross regime production losses further separated improvement under W2 from compensation for reduced irrigation. Measured yield declined from W1 to W2 by 2178.0 kg ha^{-1} for PGA, 2236.7 kg ha^{-1} for KH, 1827.9 kg ha^{-1} for BAO, and 3511.8 kg ha^{-1} for PP (Table 3). For PGA, KH, and BAO, these losses were approximately 3.4, 5.6, and 3.6 times their respective yield advantages over the untreated W2 control. The gain measured against a stressed control was therefore substantially smaller than the production deficit associated with the W1 to W2 irrigation reduction. Because each matched pair experienced the same nominal irrigation reduction of 900 m^3 ha^{-1}, the corresponding production losses were equivalent to 2.42, 2.49, 2.03, and 3.90 kg of estimated seed cotton per cubic meter of irrigation withheld for PGA, KH, BAO, and PP, respectively. BAO showed the smallest production loss per unit of irrigation saved, consistent with its highest cross regime yield retention. Similar water yield trade offs have been reported across cotton production systems, where optimized irrigation amount or frequency can improve water productivity but cannot be evaluated independently of the associated yield response [2,27,28]. The threshold analysis further quantified the remaining compensation requirement. The W2 measured yields required to maintain W1 IWP were 5247.2 kg ha^{-1} for PGA, 5097.0 kg ha^{-1} for KH, 4859.1 kg ha^{-1} for BAO, and 5242.5 kg ha^{-1} for PP. Observed W2 yields fell below these values by 866.2, 962.5, 613.1, and 2201.2 kg ha^{-1}, respectively. Relative to observed W2 production, additional yield increases of 19.8%, 23.3%, 14.4%, and 72.4% would have been required to reach the IWP maintenance boundary. BAO was therefore closest to compensation, but still required an additional 14.4% measured yield under W2.

Table 3. Independently measured seed cotton yield, absolute production losses and nominal IWP-maintenance compensation gaps for four dose-matched single-product treatments. Required W2 yield = 0.8 × W1 yield; compensation gap = required W2 yield—observed W2 yield. Values are calculated from treatment means and rounded for display.

Treatment	W1 Yield (kg ha^{-1})	W2 Yield (kg ha^{-1})	W1→W2 Loss (kg ha^{-1})	Loss per Irrigation Saved (kg m^{-3})	Required W2 Yield (kg ha^{-1})	Compensation Gap (kg ha^{-1})	Additional W2 Yield Required (%)
PGA	6559	4381	2178	2.42	5247.2	866.2	19.8
KH	6371.2	4134.5	2236.7	2.49	5097	962.5	23.3
BAO	6073.9	4246	1827.9	2.03	4859.1	613.1	14.4
PP	6553.1	3041.3	3511.8	3.9	5242.5	2201.2	72.4

These results separate three distinct dimensions of treatment performance: improvement relative to the reduced irrigation control, retention of production across irrigation regimes, and proximity to the water productivity break even boundary. Previous meta analyses have similarly emphasized that cotton responses to reduced water input are strongly management dependent and that yield and water use indicators should be interpreted jointly rather than as interchangeable measures [2,3].

Secondary Analysis of PP-Based Combinations and Dose Escalation

For the three standard-dose PP-based combinations, W2 seed cotton yield was 3719.5 kg ha^{-1} (PP + PGA; T5), 4234.2 kg ha^{-1} (PP + BAO; T6), and 4442.9 kg ha^{-1} (PP + KH; T7), compared with 6190.6 (T12), 7355.1 (T13), and 6381.0 kg ha^{-1} (T18), respectively, under W1. Yield retention across matched irrigation regimes was 60.1%, 57.6%, and 69.6%, respectively; corresponding nominal irrigation water productivity retention was 75.1%, 72.0%, and 87.0%. Thus, none of the standard-dose combinations maintained nominal irrigation water productivity across the 20% irrigation reduction. Within W2, increasing each combination to 1.5 times its component rates yielded 4511.9 kg ha^{-1} (T8), 4835.9 kg ha^{-1} (T9), and 6391.3 kg ha^{-1} (T10), equivalent to increases of 21.3%, 14.2%, and 43.9% relative to T5, T6, and T7. The formulation-specific and dose-dependent responses of seed cotton yield, yield retention, and irrigation water productivity are further illustrated in Figure S6.

3.2. Boll Number Loss Was the Dominant Component of Incomplete Production Retention

Boll number retention ranged from 52.9% to 70.5%, corresponding to losses of 29.5–47.1% after irrigation was reduced. In contrast, single boll mass retention ranged from 87.6% to 108.1%. PGA retained 94.7% of its W1 boll mass, KH essentially maintained boll mass at 101.0%, and BAO increased boll mass to 108.1%. PP was the only treatment showing substantial declines in both boll number and boll mass. This contrast between boll number and boll mass responses agrees with previous field evidence showing that boll density or boll number is often more sensitive to water limitation than individual boll mass (Figure 3a–c). Under deficit irrigation, reductions in boll number have repeatedly been identified as a major contributor to yield loss, whereas boll mass can be less responsive or partly maintained [29–31]. The contrast was especially pronounced for KH and BAO. Both retained only 64.7% of their W1 boll number, corresponding to a 35.3% loss of harvestable bolls. Nevertheless, KH maintained individual boll mass and BAO increased it by 8.1%. Their final measured yield retention remained only 64.9% and 69.9%, respectively. Maintenance or enhancement of individual boll size therefore buffered the production loss but was quantitatively insufficient to offset the reduction in boll number. Similar compensation among within boll and whole plant yield components has been observed under limited

irrigation, where improved boll biomass or within boll development can moderate, but not necessarily eliminate, losses associated with changes in boll density [29,32]. PGA showed a related but less extreme configuration. Boll number retention was highest among the four treatments at 70.5%, while boll mass retention was 94.7%. Its yield retention of 66.8% therefore reflected declines in both components, although boll number showed the larger proportional reduction. PP represented the most severe configuration, retaining only 52.9% of boll number and 87.6% of boll mass, which corresponded to the lowest yield retention of 46.4%.

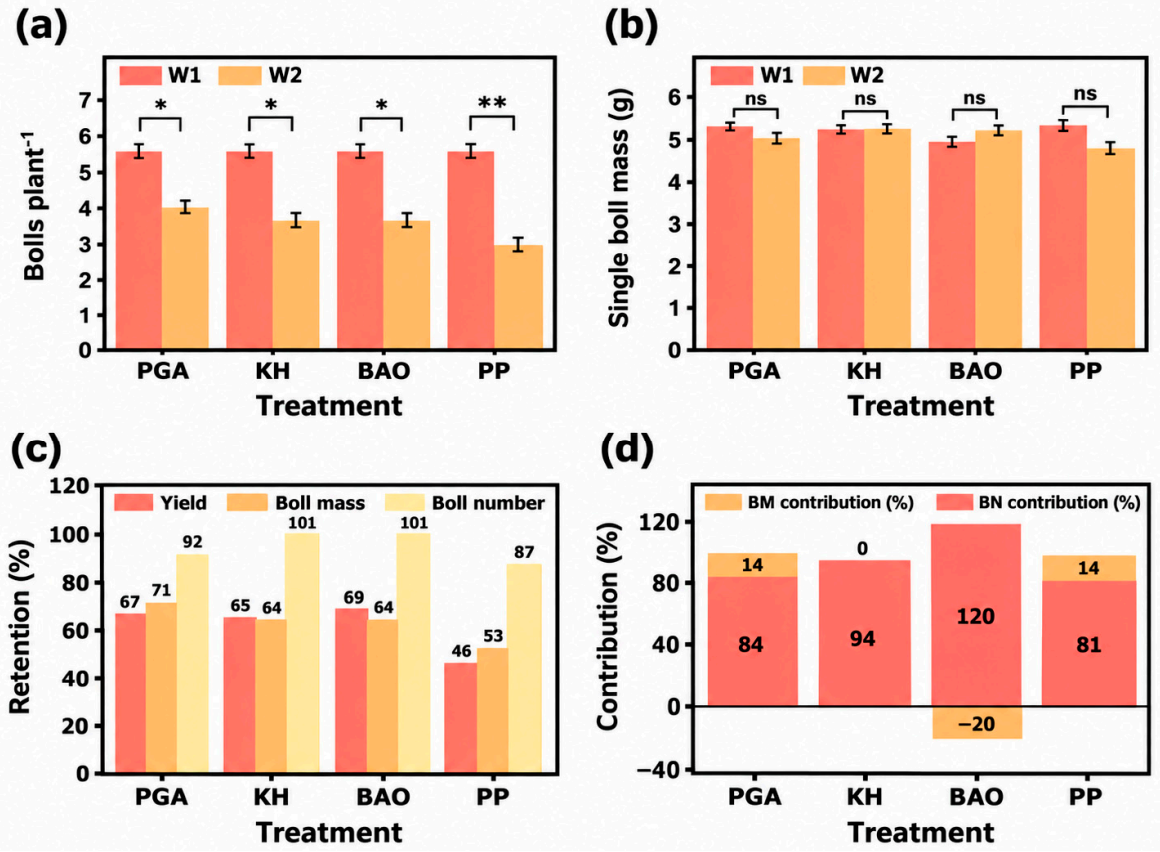

Figure 3. Yield component responses to deficit irrigation and their contributions to yield loss. (**a**) Boll number per plant under W1 and W2; (**b**) single-boll mass under W1 and W2; (**c**) retention of measured yield, boll number, and boll mass under W2 relative to W1; (**d**) logarithmic decomposition of yield loss into boll number and boll mass contributions. Negative boll mass contributions indicate partial compensation for yield loss associated with reduced boll number, whereas positive contributions indicate additional yield loss. W1 and W2 represent irrigation levels of 4500 and 3600 m^3 ha^{-1}, respectively. ** Asterisks indicate statistically significant differences between W1 and W2 (* $p < 0.05$; ** $p < 0.01$), whereas ns indicates no statistically significant difference ($p \geq 0.05$).

The product of boll-number and single-boll-mass retention provided a close descriptive approximation to independently measured yield retention. For PGA, 70.5% × 94.7% = 66.8%, matching the reported 66.8% measured retention after rounding. The corresponding component products were approximately 65.3% for KH (versus 64.9% measured), 69.9% for BAO (versus 69.9% measured), and 46.3% for PP (versus 46.4% measured). Component-based logarithmic summaries indicated that boll-number decline dominated the approximation; increases in boll mass under KH and BAO partially offset the effect of fewer bolls [33]. These component contributions should not be read as an exact decomposition of independently harvested plot yield.

3.3. Late Biomass Recovery Was Decoupled from Production Retention

Stage specific biomass responses showed that crop growth recovery differed substantially from production recovery (Table S2). At flowering boll setting, total biomass retention was 32.5% for PGA, 71.4% for KH, 41.6% for BAO, and 50.6% for PP. By boll opening, the corresponding values increased to 95.3%, 150.8%, 65.9%, and 86.8% (Figure 4a–c). PGA increased from 32.5% biomass retention at flowering boll setting to 95.3% at boll opening, a recovery of 62.8 percentage points. Despite near complete terminal biomass recovery, measured yield retention remained only 66.8%. KH showed an even larger divergence: terminal biomass reached 150.8% of W1, but measured yield retention remained at only 64.9% (Figure 4c,d; Table S7). Such divergence between biomass accumulation and reproductive output is consistent with previous cotton studies showing that biomass recovery, partitioning, and fruit retention can respond independently after reproductive loss. In particular, compensatory vegetative or whole plant growth after fruit loss does not necessarily restore the original number of reproductive structures or the associated final yield [34,35]. BAO showed the opposite ranking pattern. Its terminal biomass retention was only 65.9%, substantially below that of PGA, KH, and PP, yet it achieved the highest measured yield retention at 69.9%. PP retained 86.8% of terminal biomass but only 46.4% of measured yield. These crossed treatment rankings indicate that terminal biomass alone was not a reliable predictor of cross regime production retention.

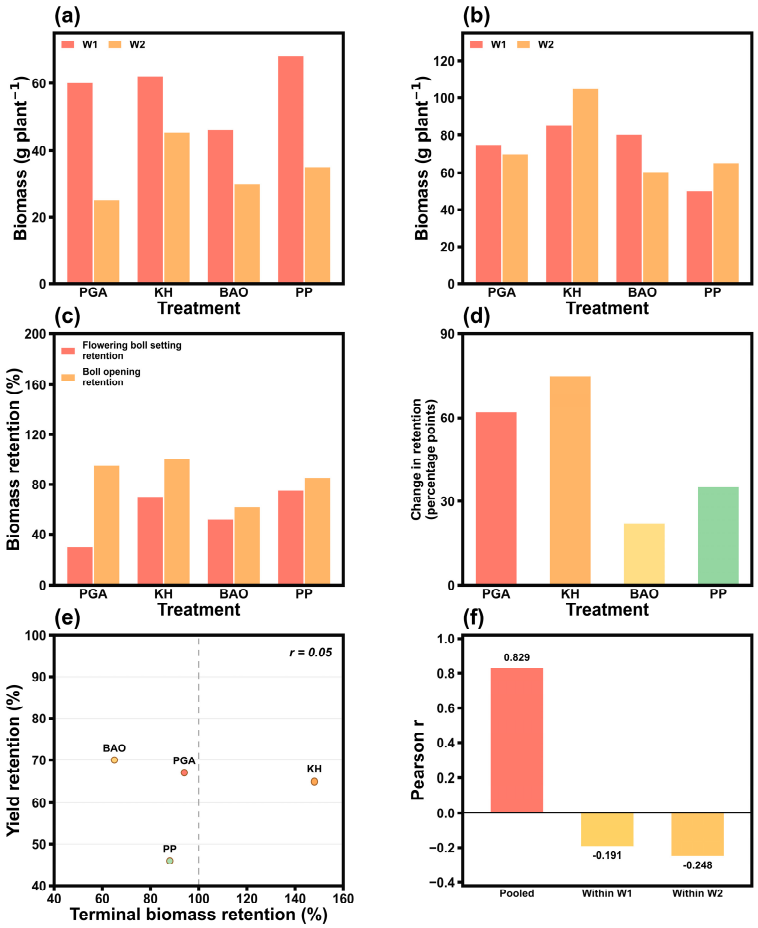

Figure 4. Temporal decoupling between biomass recovery and production retention. (**a**) Flowering–boll setting biomass under W1 and W2; (**b**) boll opening biomass under W1 and W2; (**c**) stage specific biomass retention; (**d**) change in biomass retention from flowering–boll setting to boll opening; (**e**) terminal biomass retention versus measured yield retention; (**f**) pooled and irrigation stratified biomass yield relationships, with detailed correlation diagnostics provided in Figure S3.

This temporal separation is also consistent with studies showing that the developmental timing of water shortage is critical in cotton. Deficit irrigation imposed around peak flowering or boll formation generally causes larger production penalties than comparable water shortages outside the reproductive window, indicating that late recovery in vegetative or total biomass cannot always reverse earlier reproductive losses [28,34,36]. The correlation structure supported the treatment level contrasts. When W1 and W2 treatment means were pooled, flowering stage biomass and measured yield were positively correlated ($r = 0.829$). However, corresponding within regime relationships were weakly negative in both W1 ($r = -0.191$) and W2 ($r = -0.248$). The pooled relationship therefore primarily reflected separation between irrigation regimes rather than consistent treatment level covariation within either regime (Figure S3; Table S5) [21]. Terminal biomass retention was essentially unrelated to yield retention across the four matched treatments ($r = 0.05$). Reproductive fraction likewise showed approximately zero pooled association with measured yield. Together with the treatment contrasts, these results indicate that final biomass quantity and proportional allocation did not fully represent the earlier reproductive processes determining final harvestable sink number.

3.4. Sensitivity Analyses Supported the Cross Regime Conclusions

Under W1, T11 is the untreated control and is therefore the appropriate reference for within-regime untreated-control comparisons. T18 is an active PP + KH combination and can be retained as an alternative active-treatment reference only when explicitly labeled as such (Figure 5a; Table S6). Differences between these reference choices reflect different scientific contrasts, not uncertainty about the identity of the untreated control. The four primary W1–W2 production-retention estimates remain defined by their matched single-product treatment pairs and do not depend on either reference selection.

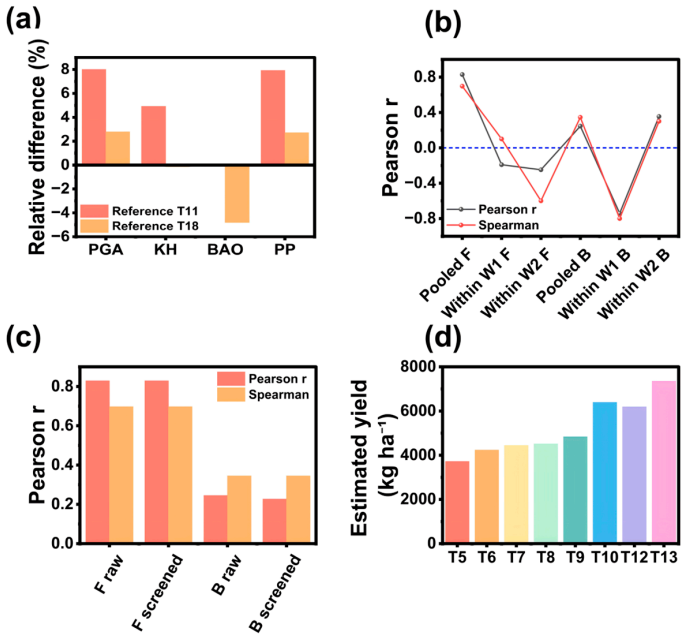

Figure 5. Sensitivity analyses and exploratory responses to biostimulant combinations. (**a**) Treatment responses under W1 relative to the untreated control (T11) and the active PP + KH treatment (T18); (**b**) Pearson and Spearman correlations across pooled and irrigation-stratified treatment means; (**c**) sensitivity of biomass responses to data screening; (**d**) responses to biostimulant combinations at standard and 1.5-fold application rates under W2. The blue horizontal dashed line in panel (**b**) indicates a correlation coefficient of zero, separating positive from negative correlations.

3.5. Integrated Response States Revealed Distinct Pathways of Incomplete Compensation

Integration of benchmark performance, yield component retention, and stage specific biomass responses showed that all four treatments remained below the same irrigation compensation boundary but reached this outcome through distinct response configurations (Figure 6; Tables 4 and S7). PGA represented the strongest within regime benefit with incomplete sink preservation. It produced the largest yield gain relative to the W2 control (+17.3%) and the highest boll number retention among the four products (70.5%). Boll mass remained relatively stable at 94.7%, and terminal biomass recovered to 95.3% of W1. Nevertheless, yield retention reached only 66.8%. KH represented late biomass recovery without corresponding reproductive recovery. Its within W2 yield response was positive (+10.7%), single boll mass was maintained at 101.0%, and terminal biomass reached 150.8% of W1. In contrast, boll number retention remained at 64.7% and measured yield retention at 64.9%. This response resembles the compensatory growth patterns reported in cotton after reproductive loss, where later biomass accumulation can increase without proportional restoration of earlier fruit retention [34]. BAO represented sink size buffering under sink number limitation. Its within W2 yield response was +13.7%, and cross regime yield retention reached 69.9%, the highest of the four treatments. BAO also increased single boll mass to 108.1% of W1, providing the clearest sink size buffering response. Comparable studies under limited irrigation have shown that management can improve boll biomass and within boll yield components even when overall yield remains constrained by other yield components [32]. PP represented combined sink number and sink size loss. Yield was 18.6% below the W2 control, boll number and boll mass retention were only 52.9% and 87.6%, respectively, and cross regime yield retention fell to 46.4%.

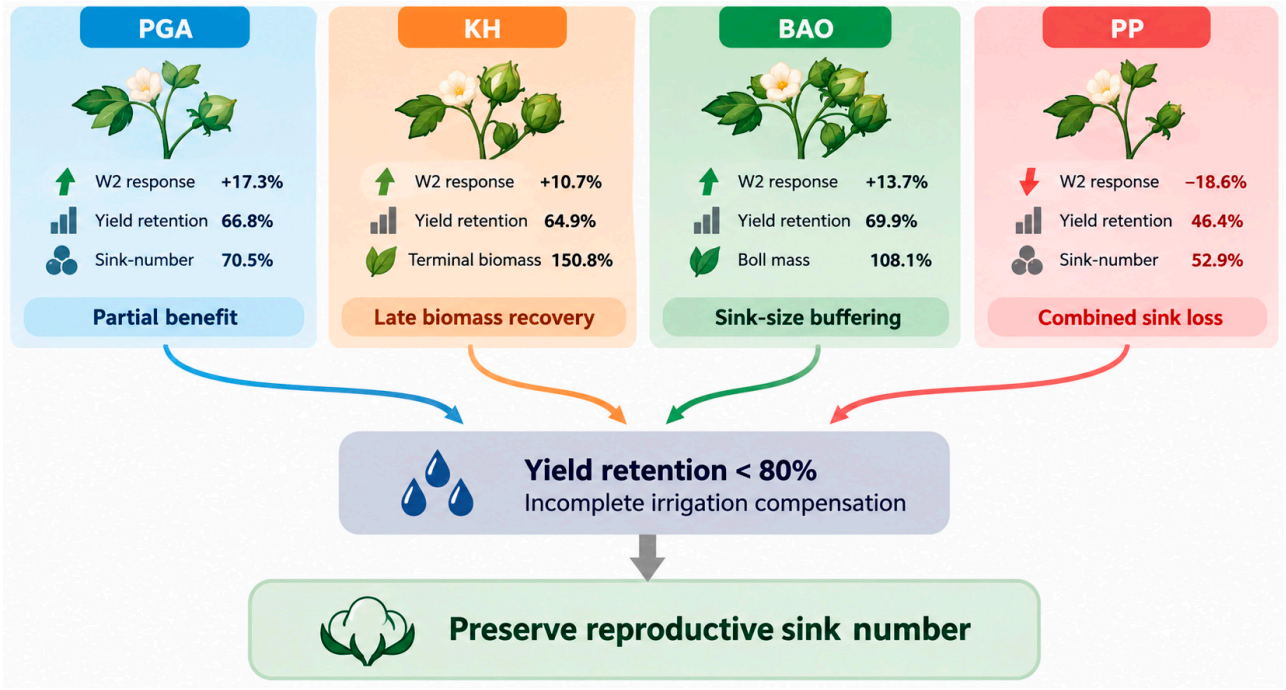

Figure 6. Integrated response state framework linking benchmark dependence, yield component constraints, temporal biomass recovery, and irrigation compensation. Product-specific pathways summarize PGA, KH, BAO, and PP responses and converge on the common outcome of yield retention below the 80% irrigation water productivity maintenance boundary. The colored curved arrows indicate the convergence of distinct biostimulant response states toward incomplete irrigation compensation, while the gray downward arrow highlights the preservation of reproductive sink number as a key target for improving irrigation compensation.

Table 4. Integrated response states and statistical evidence for the four matched biostimulant treatments.

Product	Benchmark Response	Yield Component Configuration	Biomass Retention	Integrated Response State	Compensation Outcome	Statistical Evidence
PGA	+17.3%; 66.8% retention	BN 70.5%; BM 94.7%	95.3%	Incomplete sink preservation	−13.2 pp	Within W2: **
KH	+10.7%; 64.9% retention	BN 64.7%; BM 101.0%	150.8%	Growth recovery without reproductive recovery	−15.1 pp	W1 vs. W2: *
BAO	+13.7%; 69.9% retention	BN 64.7%; BM 108.1%	65.9%	Sink size buffering under sink number limitation	−10.1 pp	Neither yield contrast significant
PP	−18.6%; 46.4% retention	BN 52.9%; BM 87.6%	86.8%	Combined sink number and sink size loss	−33.6 pp	Within W2: *; W1 vs. W2: *

Note: Statistical evidence refers to measured seed cotton yield comparisons reported in Table 2. * $p < 0.05$; ** $p < 0.01$, following Holm adjustment. Other response indicators represent descriptive treatment-mean comparisons.

Across these contrasting states, one response was common to all four products: boll number was not retained sufficiently to approach the 80% production boundary. Boll number retention ranged from only 52.9% to 70.5%, whereas three products retained at least 94.7% of single boll mass and two maintained or exceeded their W1 boll mass. Terminal biomass also varied from 65.9% to 150.8% without reproducing the ranking of yield retention. The integrated evidence therefore localized the common structural deficit to reproductive sink number, while differences in boll mass buffering and late biomass recovery determined how strongly individual treatments moderated, but did not eliminate, the resulting production loss.

4. Discussion

4.1. Benchmark Dependence Reveals Two Distinct Treatment Functions

The central result is a separation between stress regime efficacy and input substitution performance. PGA, KH, and BAO improved measured yield relative to the untreated W2 control, showing that these treatments modified crop performance within the reduced water environment. The matched W1 to W2 comparison asked a different question: whether the same product retained enough production after irrigation was reduced. None did. The apparent contradiction disappears once the treatment function is specified. A product can improve the stressed state without replacing the output lost when the resource input is withdrawn. The 80% boundary converts that distinction into a quantitative criterion. Because W2 supplied 80% of the nominal W1 irrigation, yield retention also had to reach 80% for nominal IWP to be maintained. The observed retention range of 46.4–69.9% placed every product below this boundary. BAO was closest, but its remaining gap of 613 kg ha^{-1} was still equivalent to 14.4% of its observed W2 yield. The benchmark therefore does more than label responses as positive or negative: it measures the distance between a relative benefit and a resource substitution outcome. Benchmark dependence also changed the preferred treatment. PGA ranked first for improvement relative to the W2 control, whereas BAO ranked first for matched yield retention and smallest IWP decline. This rank reversal is mechanistically informative. PGA expressed greater efficacy against the stressed untreated state, while BAO better preserved its own higher water performance. The two rankings

represent different crop response functions and should not be collapsed into one general claim of drought mitigation.

4.2. Reproductive Sink Number Loss Is the Proximal Constraint on Compensation

The yield identity located the compensation failure at reproductive sink number. Across all four products, boll number retention ranged from 52.9% to 70.5%, whereas single boll mass retention ranged from 87.6% to 108.1%. Three products therefore maintained or nearly maintained the mass of surviving bolls but still lost 30–35% of measured yield. This distinction corresponds to two different components of source–sink regulation. Boll number reflects the establishment and persistence of reproductive sinks across flowering, fruit retention, and boll survival, whereas boll mass reflects subsequent growth of the sinks that remain. Water deficit can disturb both processes, but they need not respond in parallel [14,15,37]. Earlier field studies likewise documented substantial reproductive and yield responses to water deficit across developmental stages [33,38]. The present component pattern is consistent with a crop that retained meaningful filling capacity after the reproductive sink population had already contracted. The logarithmic decomposition supports this interpretation. Boll number decline explained approximately 86.5% of the PGA loss and 82.9% of the PP loss. For BAO, the boll number term exceeded the net yield decline because the positive boll mass term offset about 22% of the loss. KH showed the same configuration at smaller magnitude. Thus, boll mass maintenance functioned as a buffer against sink number loss, not as evidence that the whole reproductive system had recovered.

4.3. Boll Mass Buffering Indicates Redistribution Among Surviving Sinks

BAO provides the clearest evidence of compensatory sink size buffering. Under W2, its boll mass increased by 8.1% while boll number declined by 35.3%. The larger surviving bolls partly reduced the yield penalty but could not overcome the missing sinks. A biologically coherent explanation is that fewer retained bolls reduced competition for assimilates, allowing more resources to be allocated to each surviving boll. Under this interpretation, increased boll mass is a consequence of a smaller sink population as well as a partial compensatory response. KH showed a weaker version of the same state: boll mass was maintained at 101.0%, but boll number retention was only 64.7%. PGA occupied an intermediate state in which both components declined, although boll mass remained close to W1. PP differed because both sink number and sink size fell, producing the lowest yield retention. These configurations show why the same final yield loss can arise from different component states and why product evaluation should report both axes rather than treating yield as a mechanistically homogeneous endpoint. The component state perspective also improves interpretation of biostimulant plausibility. Broader biostimulant reviews emphasize that field responses are strongly formulation and context dependent rather than uniform across product classes [39,40]. Poly-γ-glutamic acid has been linked with drought response regulation, rhizosphere effects, photosynthetic maintenance, soil hydro physical properties, and cotton performance under arid irrigation systems [12,13,41–45]. Humic substances can modify root and nutrient acquisition responses under water limitation [10,46–48], whereas seaweed derived materials can influence drought related signaling and stress tolerance [11,49–51]. Drought effects on subtending leaves and boll biomass further illustrate that assimilate supply to surviving bolls can remain spatially heterogeneous under stress [18,52]. Such processes may help sustain the capacity to fill surviving bolls, but maintaining filling capacity alone is insufficient when reproductive sink number falls below the level required for whole crop production retention.

4.4. Late Biomass Recovery Is Temporally Decoupled from Yield Formation

Stage specific biomass separated growth recovery from production recovery. PGA progressed from 32.5% biomass retention at flowering to 95.3% at boll opening, and KH from 71.4% to 150.8%. Neither recovered the yield associated with W1. Conversely, BAO had only 65.9% terminal biomass retention but the highest yield retention. These crossed rankings demonstrate that late dry matter accumulation and harvestable production were governed by different temporal constraints. A reproductive opportunity lost during flowering or early boll development cannot necessarily be replaced by later vegetative growth or by continued growth of a smaller number of organs. This creates a form of temporal irreversibility: later biomass can increase after the period that establishes final sink number has passed. The KH phenotype is the strongest example. Its terminal biomass exceeded W1 by 50.8%, yet yield retention was only 64.9%, indicating that additional late dry matter was not translated into enough harvestable bolls. A pooled association between flowering-stage biomass and yield, if present, may partly reflect differences between irrigation regimes rather than a stable relationship within either regime. Accordingly, the present interpretation prioritizes treatment-specific biomass and yield retention patterns; formal claims about pooled and within-regime correlations require verification using matched independent-plot observations, with the irrigation regime explicitly accounted for. Biomass alone should not be treated as a validated surrogate for reproductive sink preservation. Together, the observed component and biomass patterns are consistent with a temporal constraint on reproductive sink preservation: lower boll-number retention co-occurred with incomplete yield retention, while later biomass recovery did not necessarily restore yield. This is a plausible interpretation rather than direct proof of a causal sequence.

4.5. Product Specific Response States Integrate Efficacy and Mechanism

PGA represented stress regime benefit with incomplete sink preservation. It generated the largest yield advantage over the W2 control but did not show the highest matched retention because boll number fell to 70.5% and boll mass to 94.7%. Its response suggests that a treatment can improve the absolute W2 state without protecting enough of the higher water reproductive capacity. KH represented late growth recovery without reproductive recovery. The combination of 150.8% terminal biomass retention, 101.0% boll mass retention, and 64.7% boll number retention indicates that dry matter production and filling of surviving sinks were not the dominant limitations. The uncorrected bottleneck was the number of harvestable sinks. BAO represented the strongest sink size buffer under sink number limitation. It achieved the highest yield retention, smallest IWP decline, and smallest threshold gap while increasing boll mass. The state is promising because it reveals a partial compensatory process, but it also shows exactly why compensation remained incomplete: an 8.1% increase in boll mass was too small to offset a 35.3% loss of boll number. PP represented compound component failure. Its boll number and boll mass both declined, yielding the lowest retention and a negative response relative to the W2 control. These four states provide a more informative screening taxonomy than a single ranking because they specify whether future improvement should target general stress regime performance, reproductive sink preservation, sink filling, or both yield components.

4.6. Formulation and Dose-Dependent Responses of Combined Biostimulants Under Deficit Irrigation

The responses of the PP-based combinations extend the dual-benchmark interpretation from individual biostimulants to combined applications. Although biostimulants with different functional characteristics may provide complementary benefits under water-limited conditions, their combined application does not necessarily translate into greater agronomic

performance. At standard application rates, the three PP-based combinations retained only 57.6–69.6% of their corresponding seed cotton yields under W1, remaining below the 80% threshold required to maintain irrigation water productivity following a 20% reduction in irrigation input (Figure S6). This finding suggests that increasing the functional diversity of a biostimulant formulation alone may be insufficient to overcome the constraints imposed by limited water availability.

The contrasting responses between individual and combined applications further highlight the importance of formulation selection. Under W2, the standard-dose PP + PGA combination produced a lower mean yield than PGA alone, whereas PP + BAO produced a yield comparable to that of BAO alone. In contrast, PP + KH achieved a higher mean yield than either of its individual components. These differences suggest that the agronomic benefits of combined applications depend more on the specific formulation than simply on the number of components applied. Differences in physiological regulation, nutrient acquisition, rhizosphere processes, and interactions among bioactive components may contribute to these contrasting responses. Therefore, the potential functional complementarity of biostimulants should be evaluated in relation to actual crop performance rather than inferred solely from their individual functional characteristics.

Dose escalation revealed additional opportunities for improving the performance of combined biostimulants under deficit irrigation. Increasing the application rates of both components to 1.5 times their standard doses increased mean seed cotton yield by 21.3%, 14.2%, and 43.9% for PP + PGA, PP + BAO, and PP + KH, respectively (Figure S6). The particularly pronounced response of PP + KH suggests that the agronomic effectiveness of this formulation was sensitive to application rate within the tested range. Humic substances may promote root development and nutrient acquisition, whereas plant polyphenols may contribute to antioxidant defense and stress regulation. These potentially complementary functions provide a plausible physiological explanation for the favorable performance of PP + KH under restricted water availability. Among the three formulations, only PP + KH exhibited a statistically significant yield increase following dose escalation under W2 (43.9%, Holm-adjusted $p = 0.046$; Figure S6), highlighting its potential for application rate optimization under deficit irrigation.

From an agronomic perspective, the elevated-dose PP + KH treatment is particularly noteworthy. Under W2, this treatment achieved a mean seed cotton yield of 6391.3 kg ha^{-1} and an irrigation water productivity of 1.775 kg m^{-3}. Its mean yield exceeded that of the untreated W1 control by approximately 5.2%, despite a 20% reduction in irrigation input. This result highlights the practical potential of formulation and dose optimization for improving cotton productivity under a restricted irrigation quota. Although this comparison provides a useful agronomic benchmark, the absence of a corresponding elevated-dose W1 treatment precludes an assessment of dose-matched irrigation compensation.

Collectively, these findings highlight that the agronomic benefits of combined biostimulants are both formulation- and dose-dependent. Optimizing biostimulant combinations and application rates represents a promising strategy for improving cotton productivity under deficit irrigation. However, achieving irrigation compensation requires sufficient yield preservation relative to the corresponding full-irrigation treatment. Given the importance of reproductive sink limitation identified in this study, future formulation and dose optimization should particularly target reproductive development and the maintenance of harvestable boll number. Integrating biostimulant formulation, application rate, and reproductive-stage irrigation management may provide a more effective approach to improving cotton production under limited water availability.

4.7. Transferability and Evidence Boundary

For agricultural water management, the framework separates three decisions that are often combined: whether an amendment improves crop performance within a reduced irrigation regime, whether production retention matches the fraction of irrigation retained, and which yield component prevents closure of the water productivity gap. Earlier cotton studies across contrasting irrigation regimes, soils, and drip management strategies likewise show that yield and water productivity outcomes depend strongly on how water is supplied [53–55]. Modeling and irrigation system comparisons further demonstrate that the preferred management strategy can change with irrigation timing, delivery configuration, and the performance criterion used [56,57]. This distinction matters because a product can be agronomically useful under deficit irrigation without supporting the stronger management claim that irrigation can be reduced without sacrificing output per unit of applied water. The same accounting logic can be applied to other input reduction strategies when a matched higher input reference and a clearly defined production threshold are available.

The management implication is therefore conditional rather than prescriptive. BAO was closest to the break even boundary and showed the strongest boll mass buffering, but it still required an additional 14.4% measured yield under W2 to maintain the W1 irrigation water productivity. PGA produced the largest gain relative to the W2 control, yet its matched retention was lower than BAO. Selecting a treatment solely from performance against the reduced irrigation control would therefore favor a different product from selecting on cross regime retention. Dual reporting of relative efficacy, matched retention, and distance to the break even boundary provides a more defensible basis for deciding whether an amendment should accompany irrigation reduction.

The framework also clarifies the scale at which a water management claim is being made. The break even boundary used here evaluates output per unit of nominal irrigation applied at the treatment scale. It does not demonstrate a reduction in crop evapotranspiration, depletion of stored soil water, conveyance losses, or basin scale consumptive use. Those quantities require additional water balance measurements and cannot be inferred from the irrigation quota alone. Nevertheless, the treatment scale boundary remains useful for screening because it asks the minimum accounting question that must be satisfied before an amendment can be described as supporting irrigation reduction: did production decline more slowly than applied irrigation? In the present comparisons, the answer was no for all four products. This prevents a positive response against a stressed control from being translated directly into a claim of water saving. It also preserves a clear distinction among application efficiency, irrigation water productivity, crop water productivity, and true consumptive water savings, which operate at different system boundaries and should not be treated as interchangeable outcomes.

For future field evaluation, the dual benchmark logic can be incorporated prospectively without changing the experimental treatment structure. Each candidate amendment should be represented at both the reference and reduced irrigation levels, with untreated controls retained within each level. Predefined contrasts can then answer within regime efficacy and matched compensation separately, while direct plot harvest yield, final stand density, soil water depletion, and evapotranspiration close the remaining accounting gaps. Yield component measurements should be timed around flowering and early boll development so that loss of reproductive sinks can be separated from later filling responses. This design would test whether the response states identified here are reproducible and whether management can shift a treatment from sink size buffering to genuine preservation of reproductive sink number.

The mechanistic conclusion is intentionally located at the yield formation level supported by the data. The evidence identifies reproductive sink number retention as the

proximal constraint, boll mass maintenance as a partial buffer, and late biomass recovery as temporally decoupled from production. The dataset does not distinguish among upstream causes such as floral initiation, abscission, phenology, canopy water status, or hormonal signaling. Those processes remain alternative explanations for the observed sink number state rather than demonstrated causal pathways.

Seed cotton yield was measured from plot harvests rather than calculated from boll number and boll mass. Yield-component products were used only as a descriptive diagnostic of relative yield formation. The primary compensation calculations used treatment means and nominal irrigation quotas; statistical uncertainty and treatment-level significance require plot-level records. These distinctions do not change the definition of the 80% nominal IWP-maintenance boundary or the reported descriptive retention ratios.

Both irrigation regimes included a verified untreated control (T11 for W1 and T0 for W2), enabling within-regime comparisons against untreated crops. T18 is a W1 PP + KH combination, so contrasts involving T18 must be interpreted as active-treatment comparisons, not control effects. The principal four-product analysis remains based on matched W1–W2 single-product treatments, while combination and dose-escalation treatments constitute secondary comparisons. The unequal set of dose treatments across irrigation regimes precludes a complete factorial interpretation of all 19 treatments; formal significance testing additionally depends on verified plot-level replicate data.

5. Conclusions

Biostimulant performance under reduced irrigation was controlled by both the benchmark used and the yield component that limited recovery. PGA, KH, and BAO improved measured seed cotton yield relative to the untreated W2 control, but matched yield retention remained only 66.8%, 64.9%, and 69.9%; PP retained 46.4%. All four values were below the 80% output retention required to maintain nominal IWP after irrigation was reduced from 4500 to 3600 m^3 ha^{-1}. The mechanism of this failure converged at reproductive sink number. Boll number retention declined to 52.9–70.5%, while single boll mass retention remained at 87.6–108.1%. BAO and KH therefore buffered the loss by maintaining or increasing the mass of surviving bolls, but sink size compensation was insufficient to replace missing harvestable sinks. Terminal biomass recovery was also decoupled from production: KH reached 150.8% biomass retention but only 64.9% yield retention, showing that later dry matter accumulation did not restore an earlier reproductive deficit. The four products consequently occupied distinct response states, stress regime benefit with incomplete sink preservation, late biomass recovery without reproductive recovery, sink size buffering under sink number limitation, and compound component failure. These states explain why within regime gains did not become irrigation compensation and identify preservation of reproductive sink number as the central target for improving biostimulant enabled water saving. In the secondary combination analysis, all three standard-dose PP-based mixtures likewise remained below the 80% matched-yield-retention threshold (57.6–69.6%). Raising combination rates to 1.5 times the standard dose increased W2 treatment-mean yields by 14.2–43.9%, but the absence of matched high-dose W1 treatments prevents a claim of irrigation compensation for these treatments. These observations support targeted investigation of combination rates without altering the primary conclusion that within-W2 efficacy and cross-regime water-saving compensation are distinct outcomes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/plants15233734/s1.

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References

1. Fereres, E.; Soriano, M.A. Deficit irrigation for reducing agricultural water use. *J. Exp. Bot.* **2007**, *58*, 147–159. [CrossRef] [PubMed]
2. Cheng, M.; Wang, H.; Fan, J.; Zhang, S.; Wang, Y.; Li, Y.; Sun, X.; Yang, L.; Zhang, F. Water productivity and seed cotton yield in response to deficit irrigation: A global meta-analysis. *Agric. Water Manag.* **2021**, *255*, 107027. [CrossRef]
3. Wang, Z.; Zhang, K.; Shao, G.; Lu, J.; Gao, Y.; Song, E. Water and nitrogen use efficiencies in cotton production: A meta-analysis. *Field Crops Res.* **2024**, *309*, 109322. [CrossRef]
4. Singh, Y.; Rao, S.S.; Regar, P.L. Deficit irrigation and nitrogen effects on seed cotton yield, water productivity and yield response factor in shallow soils of semi-arid environment. *Agric. Water Manag.* **2010**, *97*, 965–970. [CrossRef]
5. Aujla, M.S.; Thind, H.S.; Buttar, G.S. Cotton yield and water-use efficiency at various levels of water and N through drip irrigation under two methods of planting. *Agric. Water Manag.* **2005**, *71*, 167–179. [CrossRef]
6. Mitchell-McCallister, D.; Williams, R.B.; Bordovsky, J.; Mustian, J.; Ritchie, G.; Lewis, K. Maximizing profits via irrigation timing for capacity-constrained cotton production. *Agric. Water Manag.* **2020**, *229*, 105932. [CrossRef]
7. Molden, D.; Oweis, T.; Steduto, P.; Bindraban, P.; Hanjra, M.A.; Kijne, J. Improving agricultural water productivity: Between optimism and caution. *Agric. Water Manag.* **2010**, *97*, 528–535. [CrossRef]
8. du Jardin, P. Plant biostimulants: Definition, concept, main categories and regulation. *Sci. Hortic.* **2015**, *196*, 3–14. [CrossRef]
9. Calvo, P.; Nelson, L.; Kloepper, J.W. Agricultural uses of plant biostimulants. *Plant Soil* **2014**, *383*, 3–41. [CrossRef]
10. Canellas, L.P.; Olivares, F.L.; Aguiar, N.O.; Jones, D.L.; Nebbioso, A.; Mazzei, P.; Piccolo, A. Humic and fulvic acids as biostimulants in horticulture. *Sci. Hortic.* **2015**, *196*, 15–27. [CrossRef]
11. Battacharyya, D.; Babgohari, M.Z.; Rathor, P.; Prithiviraj, B. Seaweed extracts as biostimulants in horticulture. *Sci. Hortic.* **2015**, *196*, 39–48. [CrossRef]
12. Xu, Z.; Ma, J.; Lei, P.; Wang, Q.; Feng, X.; Xu, H. Poly-γ-glutamic acid induces systemic tolerance to drought stress by promoting abscisic acid accumulation in *Brassica napus* L. *Sci. Rep.* **2020**, *10*, 252. [CrossRef] [PubMed]
13. Wang, Z.; Zhang, X.; Liusui, Y.; Fu, W.; Han, A.; Zhao, D.; Yue, J.; Tu, Y.; Zhang, J.; Guo, Y. Unveiling the molecular mechanisms of γ-polyglutamic acid-mediated drought tolerance in cotton through transcriptomic and physiological analyses. *BMC Plant Biol.* **2025**, *25*, 392. [CrossRef] [PubMed]
14. Pettigrew, W.T. Moisture deficit effects on cotton lint yield, yield components, and boll distribution. *Agron. J.* **2004**, *96*, 377–383. [CrossRef]
15. Lokhande, S.; Reddy, K.R. Reproductive and fiber quality responses of upland cotton to moisture deficiency. *Agron. J.* **2014**, *106*, 1060–1069. [CrossRef]
16. Sharma, B.; Mills, C.I.; Snowden, C.; Ritchie, G.L. Contribution of boll mass and boll number to irrigated cotton yield. *Agron. J.* **2015**, *107*, 1845–1853. [CrossRef]
17. McMichael, B.L.; Jordan, W.R.; Powell, R.D. Abscission processes in cotton: Induction by plant water deficit. *Agron. J.* **1973**, *65*, 202–204. [CrossRef]
18. Wang, R.; Ji, S.; Zhang, P.; Meng, Y.L.; Wang, Y.H.; Chen, B.L.; Zhou, Z.G. Drought effects on cotton yield and fiber quality on different fruiting branches. *Crop Sci.* **2016**, *56*, 1265–1276. [CrossRef]

19. Bange, M.P.; Milroy, S.P. Timing of crop maturity in cotton: Impact of dry matter production and partitioning. *Field Crops Res.* **2000**, *68*, 143–155. [CrossRef]
20. Bange, M.P.; Milroy, S.P. Growth and dry matter partitioning of diverse cotton genotypes. *Field Crops Res.* **2004**, *87*, 73–87. [CrossRef]
21. Schober, P.; Boer, C.; Schwarte, L.A. Correlation coefficients: Appropriate use and interpretation. *Anesth. Analg.* **2018**, *126*, 1763–1768. [CrossRef] [PubMed]
22. Gelman, A.; Stern, H. The difference between "significant" and "not significant" is not itself statistically significant. *Am. Stat.* **2006**, *60*, 328–331. [CrossRef]
23. Hurlbert, S.H. Pseudoreplication and the design of ecological field experiments. *Ecol. Monogr.* **1984**, *54*, 187–211. [CrossRef]
24. Nakagawa, S.; Cuthill, I.C. Effect size, confidence interval and statistical significance: A practical guide for biologists. *Biol. Rev.* **2007**, *82*, 591–605. [CrossRef] [PubMed]
25. Hedges, L.V.; Gurevitch, J.; Curtis, P.S. The meta-analysis of response ratios in experimental ecology. *Ecology* **1999**, *80*, 1150–1156. [CrossRef]
26. Papastylianou, P.T.; Argyrokastritis, I.G. Effect of limited drip irrigation regime on yield, yield components, and fiber quality of cotton under Mediterranean conditions. *Agric. Water Manag.* **2014**, *142*, 127–134. [CrossRef]
27. Zhi, X.; George-Jaeggli, B.; Han, Y.; Chen, Q.; Zhang, S.; Feng, L.; Lei, Y.; Li, X.; Wang, G.; Wang, Z.; et al. Comprehensive analysis on investigating water-saving potentials of irrigated cotton in semi-arid area in China. *Agric. Water Manag.* **2024**, *301*, 108960. [CrossRef]
28. Himanshu, S.K.; Fan, Y.; Ale, S.; Bordovsky, J. Simulated efficient growth-stage-based deficit irrigation strategies for maximizing cotton yield, crop water productivity and net returns. *Agric. Water Manag.* **2021**, *250*, 106840. [CrossRef]
29. Hu, W.; Snider, J.L.; Wang, H.; Zhou, Z.; Chastain, D.R.; Whitaker, J.; Perry, C.D.; Bourland, F.M. Water-induced variation in yield and quality can be explained by altered yield component contributions in field-grown cotton. *Field Crops Res.* **2018**, *224*, 139–147. [CrossRef]
30. Hou, X.; Li, H.; Ding, R.; Du, T. Hydraulic, morphological, and anatomical changes over the development of cotton bolls and pedicels leading to boll opening under well-watered and water deficit conditions. *Environ. Exp. Bot.* **2024**, *228*, 105996. [CrossRef]
31. Cordeiro, C.F.S.; Raphael, J.P.A.; Echer, F.R. Boll distribution in the cotton canopy is affected by nitrogen management and cover crops in a sandy soil under water scarcity. *Field Crops Res.* **2024**, *306*, 109209. [CrossRef]
32. Shi, X.; Hao, X.; Yang, Y.; Li, N.; Shi, F.; Tian, Y.; Zhang, H.; Li, H.; Liu, P.; Wang, J.; et al. Enhancing cotton yield and fiber quality via the optimization of within-boll yield components with potassium application under limited drip irrigation in arid regions. *Ind. Crops Prod.* **2024**, *222*, 119957. [CrossRef]
33. Gerik, T.J.; Faver, K.L.; Thaxton, P.M.; El-Zik, K.M. Late season water stress in cotton: I. Plant growth, water use, and yield. *Crop Sci.* **1996**, *36*, 914–921. [CrossRef]
34. Grundy, P.R.; Yeates, S.J.; Bell, K.L. Cotton production during the tropical monsoon season. II—Biomass accumulation, partitioning and RUE in response to boll loss and compensation. *Field Crops Res.* **2020**, *255*, 107868. [CrossRef]
35. Sadras, V.O. Compensatory growth in cotton after loss of reproductive organs. *Field Crops Res.* **1995**, *40*, 1–18. [CrossRef]
36. Bista, M.K.; Adhikari, B.; Sankarapillai, L.V.; Pieralisi, B.; Reddy, K.R.; Jenkins, J.; Bheemanahalli, R. Drought and heat stress induce differential physiological and agronomic trait responses in cotton. *Ind. Crops Prod.* **2024**, *222*, 119540. [CrossRef]
37. Herritt, M.T.; Thompson, A.; Thorp, K. Irrigation management impacts on cotton reproductive development and boll distribution. *Crop Sci.* **2022**, *62*, 1559–1572. [CrossRef]
38. McMichael, B.L.; Hesketh, J.D. Field investigations of the response of cotton to water deficits. *Field Crops Res.* **1982**, *5*, 319–333. [CrossRef]
39. Yakhin, O.I.; Lubyanov, A.A.; Yakhin, I.A.; Brown, P.H. Biostimulants in plant science: A global perspective. *Front. Plant Sci.* **2017**, *7*, 2049. [CrossRef] [PubMed]
40. Rouphael, Y.; Colla, G. Toward a sustainable agriculture through plant biostimulants: From experimental data to practical applications. *Agronomy* **2020**, *10*, 1461. [CrossRef]
41. Ma, H.; Li, P.; Liu, X.; Li, C.; Zhang, S.; Wang, X.; Tao, X. Poly-γ-glutamic acid enhanced the drought resistance of maize by improving photosynthesis and affecting the rhizosphere microbial community. *BMC Plant Biol.* **2022**, *22*, 11. [CrossRef] [PubMed]
42. Zhai, Z.; Shi, W.; Liu, L.; Jing, B. Effects of poly-γ-glutamic acid on soil pore structure, maize grain filling, yield and water-use efficiency under mulched drip irrigation. *Field Crops Res.* **2024**, *317*, 109528. [CrossRef]
43. Guo, J.; Shi, W.; Li, J.; Zhai, Z. Effects of poly-γ-glutamic acid and poly-γ-glutamic acid super absorbent polymer on the sandy loam soil hydro-physical properties. *PLoS ONE* **2021**, *16*, e0245365. [CrossRef] [PubMed]
44. Liang, J.; Shi, W.; He, Z.; Pang, L.; Zhang, Y. Effects of poly-γ-glutamic acid on water-use efficiency, cotton yield, and fiber quality in the sandy soil of southern Xinjiang, China. *Agric. Water Manag.* **2019**, *218*, 48–59. [CrossRef]
45. Liu, M.; Zheng, J.; Zhang, J.; Yin, F.; Javed, T.; Wen, Y.; Wang, Z. γ-Polyglutamic acid–irrigation coupling strategy to improve soil quality, microbial activity, and cotton yield within arid saline-alkali fields. *Agric. Water Manag.* **2026**, *329*, 110361. [CrossRef]

46. Rose, M.T.; Patti, A.F.; Little, K.R.; Brown, A.L.; Jackson, W.R.; Cavagnaro, T.R. A meta-analysis and review of plant-growth response to humic substances: Practical implications for agriculture. *Adv. Agron.* **2014**, *124*, 37–89. [CrossRef]
47. Jindo, K.; Olivares, F.L.; da Paixão Malcher, D.J.; Sánchez-Monedero, M.A.; Kempenaar, C.; Canellas, L.P. From lab to field: Role of humic substances under open-field and greenhouse conditions as biostimulant and biocontrol agent. *Front. Plant Sci.* **2020**, *11*, 426. [CrossRef] [PubMed]
48. Yang, M.H.; Zhang, L.; Xu, S.T.; McLaughlin, N.B.; Liu, J.H. Effect of water soluble humic acid applied to potato foliage on plant growth, photosynthesis characteristics and fresh tuber yield under different water deficits. *Sci. Rep.* **2020**, *10*, 7854. [CrossRef] [PubMed]
49. Sharma, S.; Chen, C.; Khatri, K.; Rathore, M.S.; Pandey, S.P. Gracilaria dura extract confers drought tolerance in wheat by modulating abscisic acid homeostasis. *Plant Physiol. Biochem.* **2019**, *136*, 143–154. [CrossRef] [PubMed]
50. Jacomassi, L.M.; Viveiros, J.O.; Oliveira, M.P.; Momesso, L.; de Siqueira, G.F.; Crusciol, C.A.C. A seaweed extract-based biostimulant mitigates drought stress in sugarcane. *Front. Plant Sci.* **2022**, *13*, 865291. [CrossRef] [PubMed]
51. Mannan, M.A.; Yasmin, A.; Sarker, U.; Bari, N.; Dola, D.B.; Higuchi, H.; Ercisli, S.; Ali, D.; Alarifi, S. Biostimulant red seaweed extracts spray improves yield and drought tolerance in soybean. *PeerJ* **2023**, *11*, e15588. [CrossRef] [PubMed]
52. Zhao, W.Q.; Wang, R.; Hu, W.; Zhou, Z.G. Spatial difference of drought effect on photosynthesis of leaf subtending to cotton boll and its relationship with boll biomass. *J. Agron. Crop Sci.* **2019**, *205*, 263–273. [CrossRef]
53. Hussein, F.; Janat, M.; Yakoub, A. Assessment of yield and water use efficiency of drip-irrigated cotton (Gossypium hirsutum L.) as affected by deficit irrigation. *Turk. J. Agric. For.* **2011**, *35*, 611–621. [CrossRef]
54. DeTar, W.R. Yield and growth characteristics for cotton under various irrigation regimes on sandy soil. *Agric. Water Manag.* **2008**, *95*, 69–76. [CrossRef]
55. Dağdelen, N.; Başal, H.; Yılmaz, E.; Gürbüz, T.; Akçay, S. Different drip irrigation regimes affect cotton yield, water-use efficiency and fiber quality in western Turkey. *Agric. Water Manag.* **2009**, *96*, 111–120. [CrossRef]
56. Ritchie, G.L.; Whitaker, J.R.; Bednarz, C.W.; Hook, J.E. Subsurface drip and overhead irrigation: A comparison of plant boll distribution in upland cotton. *Agron. J.* **2009**, *101*, 1336–1344. [CrossRef]
57. Baumhardt, R.L.; Colaizzi, P.D.; Howell, T.A.; Staggenborg, S.A.; Gowda, P.H. Modeling irrigation management strategies to maximize cotton lint yield and water-use efficiency. *Agron. J.* **2009**, *101*, 460–468. [CrossRef]

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